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Modular DC-DC Power Converter for Robotic Applications

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Nashua Circuits Inc. http://www.ncipcb.com

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Texas Instruments http://www.ti.com/

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Tyco Electronics http://www.tycoelectronics.com

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Cooper Bussmann http://www.cooperbussmann.com/

Vishay http://www.vishay.com/

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Analog Devices http://www.analogdevices.com

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Abstract

This project details the design process, construction, and testing of a high current DC to DC switch mode power supply. The power supply utilizes a wide range input voltage from 18 volts to 40 volts to create stable 12 volt, 5 volt, and 3.3 volt supplies at a maximum load current of 20 amps per supply. These specifications meet the computer requirements for existing robot applications that run on 24V DC battery systems.

Executive Summary

It has been brought to our attention that there is a growing need for a stable, efficient, and versatile 24 volt power supply in the WPI community. Many MQP groups and externally sponsored projects are building robotic systems that require the use of two 12V car batteries for mobility and a long operating lifetime. In most of these groups there is either not enough budget or time to provide a deep look into the power requirements for their system. Seeing as most robotic systems incorporate multiple modules together to run the entire system, power to all of the robot's modules would relieve the concern for a power system design. This project attempts to eliminate the requirement of a power design in these systems by creating a highly efficient supply capable of providing 3.3V, 5V, and 12V outputs each capable of supplying up to 20 amps from a single 24V DC input. The power supply design utilizes three synchronous buck converters similar to the one shown in Figure 3.

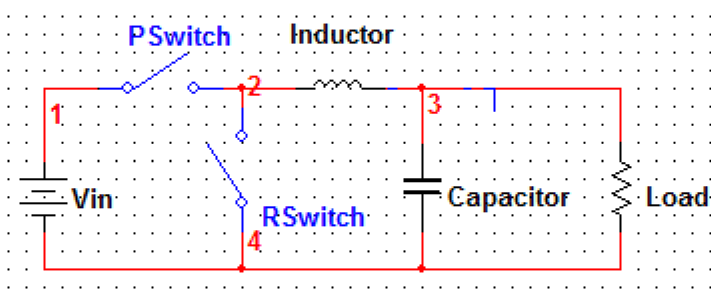

Figure 3-Synchronous Buck Converter Schematic

Basic operation of the circuit is as follows. Switches P and R control the duty cycle of the input, which is proportional to the desired output voltage. The inductor and capacitor are energy storage elements that form a second order low-pass filter with a cut-off frequency well below the switching frequency of the supply. In this way, a smooth filtered DC voltage is supplied to the load. Using the requirements of the Prometheus Autonomous Vehicle MQP as a basis for the design, the following design criteria were created:

Input Voltage (V)	Current Draw (A)	Output Voltages (V)	Current Output (A)
24	20	12	20
		5	20
		3.3	20

Table 1-Electrical Design Criteria

After comparing many different switcher ICs, the Texas Instruments' TPS40055 was chosen due to its availability, versatility and online support. Using a design tool available on TI's website, the chip could be applied in a schematic presented below in order to achieve the desired functionality:

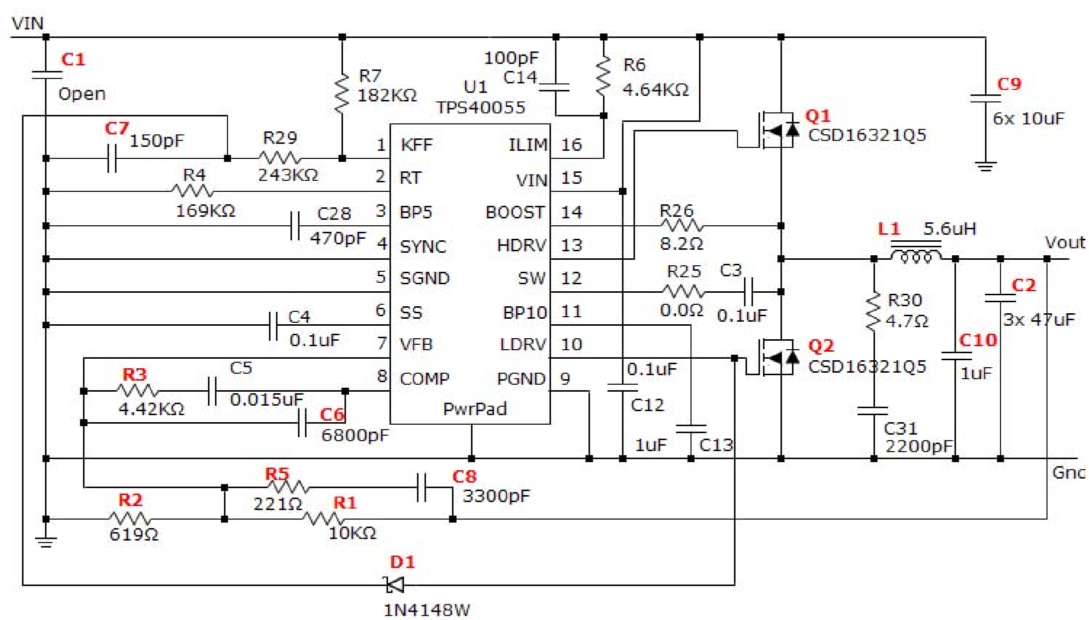

Figure 4: 24 to 12 Volt Converter

Ignoring many of the extra features on the chip, the two switches (Q1 and Q2), the inductor (L1), and capacitor (C2/10) can be seen on the right side of the circuit, just like Figure 1. The other inputs and outputs to the chip control various other features such as over-current protection, smooth startup, and feedback networks.

Thermally, the circuit in Figure 4 only has a few components through which significant amounts of current flow. The two MOSFETs and the inductor have all of the output current flow through them on a regular basis and thus require some thermal considerations. The design tool from TI calculated that the highest temperature reached is the Q2 on the 3.3V rail under full load with the temperature of 120^{o}C. One very efficient way of lowering this temperature is to choose a package size that contains a thermal pad on the bottom of the chip. In the board layout this thermal pad will connect to the copper planes within the board in order to dissipate heat. In addition to the thermal layers in the board, a simple fan circuit was added to move heat away from the board.

Taking into account the thermal considerations, the desire for surface mount components, and current requirements, a board layout was created to handle as much current as necessary. The board was created with four copper layers to help dissipate the amount of heat that could potentially arise as well as thermal reliefs to allow for even more heat dispersion. The entire system was designed to fit into the standard form factor for existing ATX power supplies including input and output connections and cooling fans.

The initial testing began with a bench-top power supply to provide up to three amps to the input and a resistive bank for a load. For the higher power tests the power supply was changed for two car batteries and light bulbs as loads. From these different loads, a series of input and output measurements were taken to measure the efficiencies:

12V @ 10A Efficiency	98.61%
5V @ 10A Efficiency	89.32%
5V @ 1A Efficiency	74.83%
3.3V @ 1A Efficiency	66.14%

Table9: Efficiencies of Power Supplies

Despite some testing and troubleshooting issues, the project worked as expected and in producing a 3.3V, 5V, and 12V output voltage at the desired current ratings. The efficiencies in the table above are lower than expected because of the low current draws as well as some of the problems that were encountered in testing.

Overall, this project has some fine points that need to be fixed, but as a basic power supply, it works very well at being incredibly efficient, mobile, and stable. The form factor of a standard ATX power supply allows for high mobility while still allowing enough thermal relief for proper functionality. The overall design has shown the potential for excellent efficiency depending on load and proper components and has little to no instability even during high amounts of load.

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Safety

Safety is a primary concern when dealing with power supplies, especially involving high voltage and/or high current. There are some precautions that can be taken in order to limit any dangers to the device or the user.

This power supply contains integrated circuits that are made with MOSFET technology. It is extremely important to take proper electrostatic discharge precautions while assembling and handling the device as not to inadvertently cause damage to the system. Damage from ESD can be prevented by wearing a properly grounded ESD strap as well as working on an ESD safe surface.

Heat generated is also of concern when working around power supplies. Precaution should be taken as to not touch the circuitry while it is operating as the MOSFETs are capable of reaching external temperatures capable of causing burns. To avoid injury, care should be taken not to touch any MOSFETs during circuit operation or directly after powering down. Allow for a short period of time to allow for cooling.

Care must also be taken when working around the power supply after it has been powered off if it was not connected to a load at the time of shutdown. The output has a high RC time constant and will take significant time to disgorge when powered down. One can either discharge the capacitors by shorting the output to ground AFTER the power supply is turned off or waiting for the natural RC discharge to occur.

To remain within safe operating conditions, output connections to the board should not be modified while the power supply is in operation. Hot swapping outputs has can possibly damage the circuitry by causing a rapid change in voltage levels, which is capable of causing instability in the power supply. If output connections need to be broken during power supply operation, switches should be used. These simple precautions will keep the user safe as well as preventing any damage to the device.

I – Introduction

Objective

Our goal with this project is to address the growing issue of direct current (DC) power within in the WPI robotics community. By creating a small, versatile, and efficient student designed power supply groups can efficiently utilize their 24 Volt battery source while retaining stability, a parallel system design, and a long lifespan. This design also allows the addition of prebuilt modules including cameras, GPS systems, routers, and computers to their design with minimal thought into the power system.

Background

One specific practical use would be the Prometheus Major Qualifying Project (MQP) Team. Prometheus is, "WPI's first entry to the Intelligent Ground Vehicle Competition," which, "challenges students to build and program a fully autonomous [unmanned ground vehicle] that can locate and avoid obstacle, stay within the boundaries of a lane, navigate to GPS waypoints and implement a communications system using the Joint Architecture for Unmanned Systems (JAUS) protocol."[1] This robot is a large complicated system that requires a 24V battery system to run various modules and sensors to accomplish its goal.

Our project worked very closely with the Prometheus group in order to determine some of the requirements that they would like to see in their power system. Meetings with the group as seen in the Meeting Minutes in Appendix F describe the desires of the group from which we came up with a list of questions regarding their desires for a new supply. These questions can be seen in Appendix B.

Through discussion with Prometheus' project advisor and electrical engineering student, we determined that the group wanted the system as small as possible while maintaining the existing performance. The existing model was a 24V DC input computer power supply, which was expensive due

[1] (Justin Barrett, 2010)

to the power requirement (750W) and specialty order status. One of the main problems that the Prometheus group was facing was that in order to retrieve different voltages to run modules they were splitting power off the computer supply, making the system unorganized.

Taking into account the various aspects that were desired, our group decided on some basic design qualities. The first quality that we wished to cover was power requirements. Instead of making a system to replace the 750W power supply, we decided to focus on a smaller more versatile system that would allow additional modules to be added without effort. By taking a smaller approach, we are able to power the processing card on the Prometheus' on-board computer, which allows Prometheus to purchase a cheaper, smaller computer power supply. Taking this approach means the Prometheus team only needs to purchase two to three small power supplies as opposed to one large, expensive one to run their system.

Switching Power Supplies

Power supplies are a necessary component in almost all modern electronics. These devices are required to regulate in the input voltage to a system to the required outputs. This is necessary due to many factors that can affect input to a system. These issues can be overvoltage, voltage drop, oscillation, spikes and other instabilities. The power supply attempts to correct all of these issues and maintain a clean stable output no matter the input. [2]

Another potential problem that must be kept in mind when using a power supply is that such a device is never 100 % efficient and some power must be sacrificed to operate the supplies own circuitry. There are also losses that are due to the shortcomings of real world components such as resistance across inductors, and the switches used in the power supply. To increase

[2] (National Semiconductor, 2002)

The type of power supply that is most easily utilized for a direct current to direct current conversion is a pulse width modulation type supply, or also known as a switching power supply. This type of supply consists of a few system blocks. Figure 1 shows a block diagram explaining the flow of the system and the feedback elements included in it.

The two most common switch-mode power supply topologies are the Buck and Boost topologies. The Boost topology is used when the required output is lower than the given input. The Buck topology is used when the required outputs are below the available input. In the case of this project, the design will rely on the Buck topology. The reason for this will be made clearer in the design section of the report. The next section includes a more in-depth investigation into the operation of a buck converter and the benefits and drawbacks associated with it.

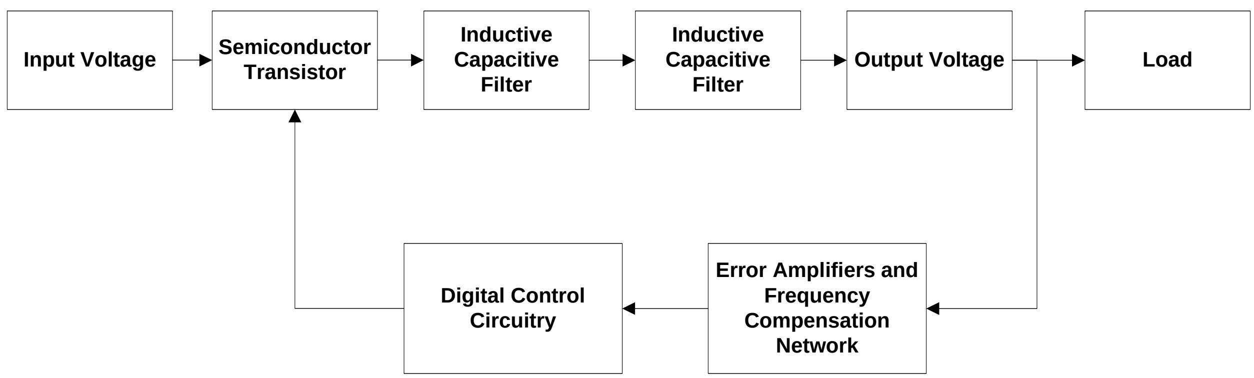

Figure 1- Switching Power Supply System Block Diagram

Buck Topology Power Supplies

The first type of buck converter is the simpler standard design. This consists of an input voltage, fed through a switch. Generally, this switch is a MOSFET controller by an integrated circuit. The rest of the circuit consists of an inductor, a diode, a capacitor, and the load. In this case, a resistor models the load but this load can be non-linear. The switch is pulsed at an adjustable duty cycle to achieve a voltage across the load. The simple schematic of this circuit can be found in Figure 2.

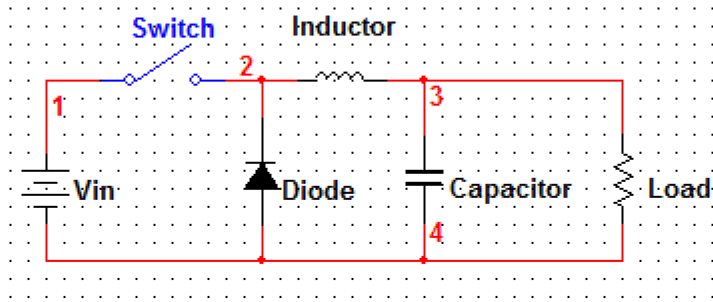

Figure 2-Standard Buck Converter Schematic

This design has a few equations that can be used to determine the relations of voltage in to voltage out and current in to current out. The voltage is primarily determined by the duty cycle, and the frequency of the driving signal allows for the use of different valued inductors and capacitors. This analysis will assume ideal conditions for the circuit to simplify equations in a more useable manner.

The following equations describe the operation of the buck converter by splitting it into two separate states, one with the PSwitch on with conduction through switch, through inductor into the capacitor and load, and the off cycle with the diode acting as the conductor, conduction through the inductor and current draw from the capacitor to supply the load. These Equations also assume a continuous mode operation of the buck converter, meaning that the load is great enough that constant switching must be maintained to regulate the output voltage.

$$E_L = \frac{1}{2} L * {I_L}^2$$

Equation 1-Energy Stored In Inductor

$$V_L = L \frac{dI_L}{dt}$$

Equation 2-Voltage Across Inductor

$$V_o = \frac{t_{on}}{T} * V_i$$

Equation 3-Relation of Vout to Vin

$$D = \frac{t_{on}}{T}$$

Equation 4- Definition of Duty Cycle[3]

$$D = \frac{V_o}{V_i}$$

Equation 5-Duty Cycle to Ratio of V_{in} to V_{out}

The topology can easily be modified to increase the efficiency of operation. This is realized by replacing the diode with another MOSFET. This reduces losses from the voltage drop across the diode and makes the circuit a more ideal system. The operation of the switches can be explained as, when PSwitch is closed, RSwitch is open, and when RSwitch is closed, PSwitch is open. This schematic can be seen in Figure 3.

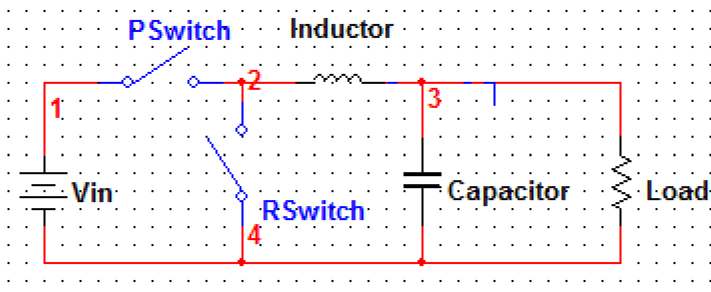

Figure 3-Syncronous Buck Converter Schematic

Using these ideas, a power supply that suites both the needs of Prometheus as well as future needs of robotics projects must be created. The power supply designed in this case will be a buck topology converter, as the output will have a lower voltage than the input. The next chapter details the design process for both the mechanical and electrical design of the system.

[3] (National Semiconductor, 2002)

II – Design

Design Criteria

Electrical Characteristics

The design for this power supply has two primary goals that must be met. The first is to meet the needs of the Prometheus Autonomous Vehicle MQP. The second is to remain useful for other projects that also require a robust DC-to-DC converter.

The primary need of Prometheus is a power supply to supply the video processing card. The video processing card is a NVIDIA Tesla C1060 requiring a maximum of 187.8 Watts. More specifically this supply must power the auxiliary power input that is not supported by the PCI-Express card slot.

To support the needs of other projects more utility must be added then just a single 12-volt rail as an output. Other common outputs include 5 and 3.3-volt outputs. These were both chosen to be added to the design criteria of this supply.

The next criteria that needed to be determined was the input voltage that was available for the supply to use. In the case of Prometheus, a 24-volt supply was the only available supply voltage. Knowing this the most sensible option to choose for a topology would be a buck type supply. Given these requirements a set of specifications where created to provide a design criteria from which to create the supply.

Input Voltage (V)	Current Draw (A)	Output Voltages (V)	Current Output (A)
24	20	12	20
		5	20
		3.3	20

Table 1-Electrical Design Criteria

Mechanical Characteristics

There are two main design goals for the mechanical aspects of this power supply. One is to keep the power supply as small and light as possible. Space in the electronics compartment of Prometheus is at a premium and on most robotic platforms; space and weight must be taken into consideration for every component. The footprint of the power supply with be kept as small as possible, but it is also a goal to attempt to adhere to a standard form factor, to keep the possible applications of this power supply very broad. The decision was made to stick to the footprint of a standard ATX PC power supply, while keeping the height as small as possible.

The second primary mechanical design goal is to keep heat in check. Switching power supplies, while more efficient than linear supplies, still contain components that generate large amounts of heat. With a combination of passive and active cooling, the goal is to keep the power supply running at an efficient temperature and ensuring long component life.

Methods

Electrical

The most thorough option to choose for the design of this power supply would be to build the entire supply from the ground up including the switching controller circuitry. This is a time and labor-intensive process. Given the limited time, budget, and scope of this project this design method was not chosen.

The second option would be to choose a switcher controller integrated circuit from one of the many IC manufacturers. This is a much simpler method as all of the required logic, comparators, and amplifiers are contained within the IC. Another benefit of using this method is the massive amount of documentation and design tools available on the internet and the website of the manufacturer for achieving your requirements.

Mechanical

Because size and weight is of utmost concern, the case of the power supply will be designed and fabricated from sheet metal. While time consuming, this will result in a well designed layout within the case that wastes little space and does not add any unnecessary weight to the robotic application the power supply might be utilized in.

The Design

Electrical

Using the design criteria and chosen method research was done into different company's possible solutions. The first company to be investigated was Linear Technology. A few of their integrated circuit solutions were capable of meeting the needs of this design. There were issues with their parts though. First, many of their parts contained functionality that far exceeded the requirements of this supply. Second, there was no single Integrated Circuit that could be used as the controller chip for all three-output rails.

The second company to be considered was Analog Devices. They were not a good choice as their products were not capable of handling the power ratings that were required by this device.

The third company, Texas Instruments, had major advantages over the competition. The first advantage was their free design tool Switcher Pro. It was easy to use, available after only a brief registration for an account, and included almost all of the switcher controller solutions the company had to offer. Using this design tool one integrated circuit appeared to be a good choice for this design. The TI TPS40055 met the input and range of outputs with much of the same required discrete components. The first converter to be designed was the 24 to 12 Volt converter.

After determining the switching chip that could perform adequately, the three converter circuits (Figures 4, 5, and 6) were created using Texas Instruments' Switcher Pro design tool. Taking the complexities, the converter circuits are mirror images of Figure 3, the Synchronous Buck Converter. For example, inductor L1 in Figure 4 acts as the inductor from Figure 3, capacitors C2 and 10 as the capacitors, resistor R30 as the resistor, and Q1 and Q2 as the PSwitch and RSwitch respectively.

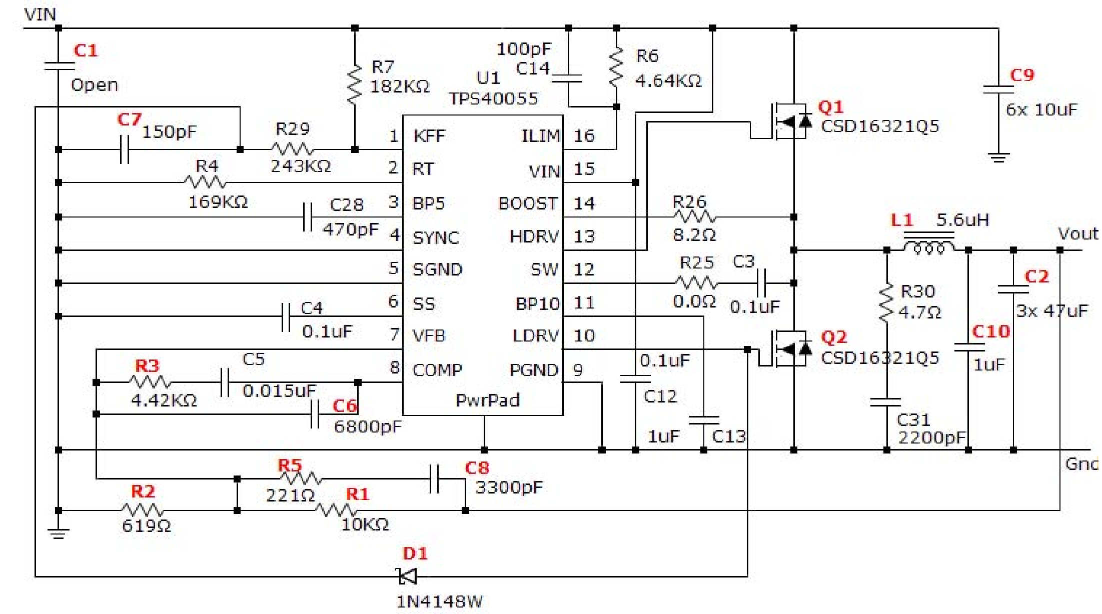

Figure 4-24 to 12 Volt Converter

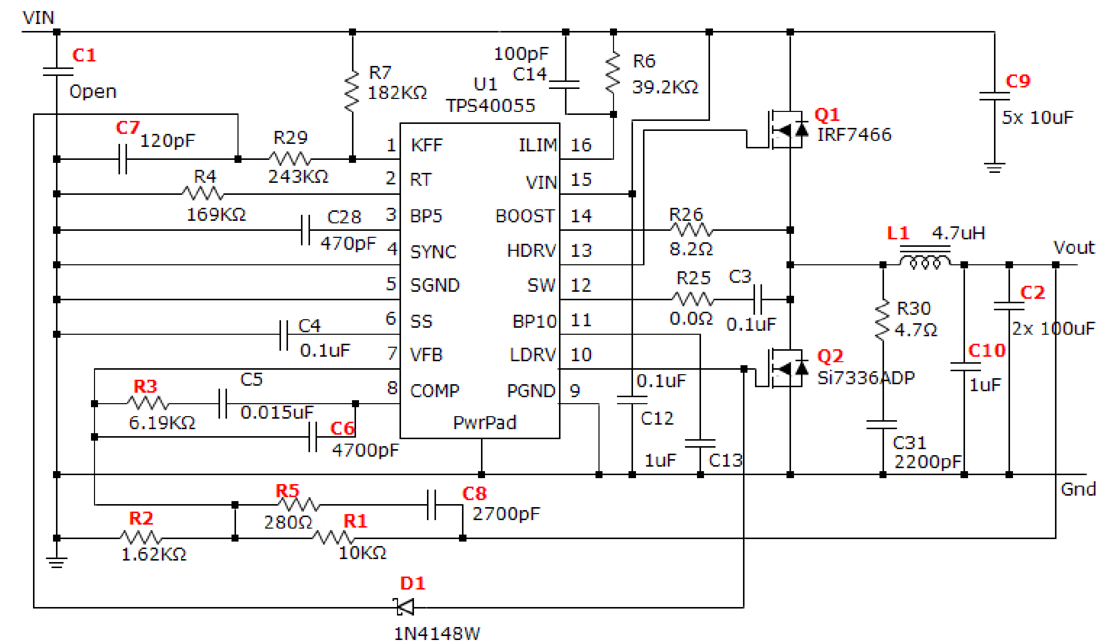

Figure 5-24 to 5 Volt Converter

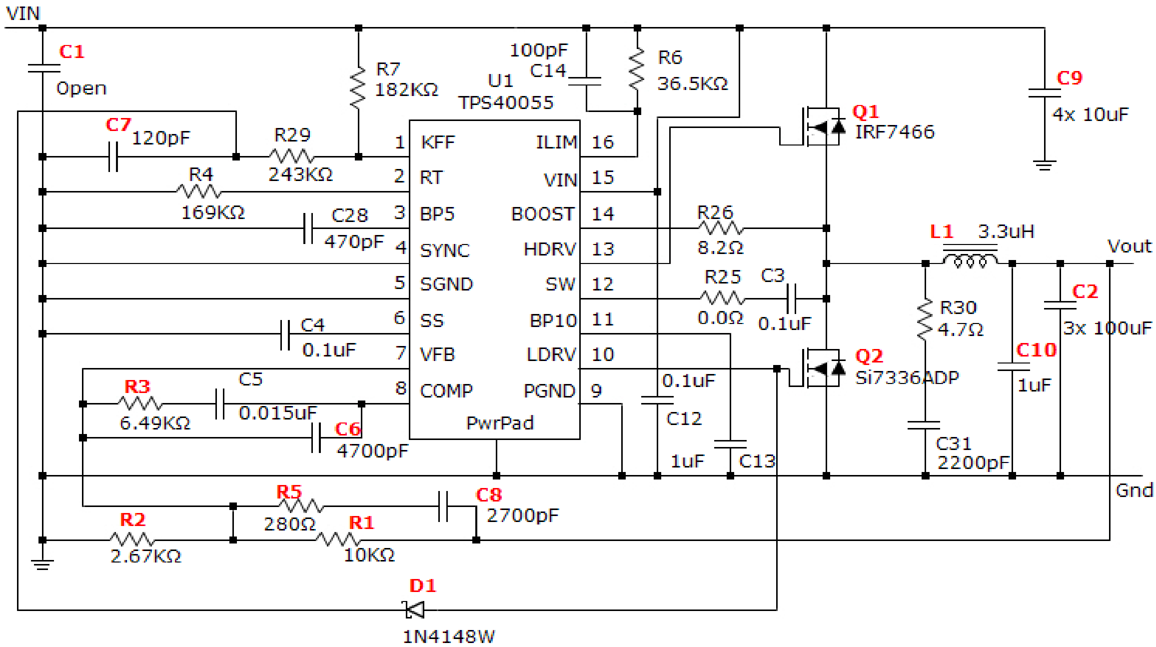

Figure 6-24 to 3.3 Volt Converter

Taking into account the simple nature of the converting circuits, we can look into more of the sophistications of the TPS40055 chip, (Texas Instuments, 1995-2010), as well as the extra components in figure 7. This extra circuitry allows for stable, efficient operation, at a variety of input voltages.

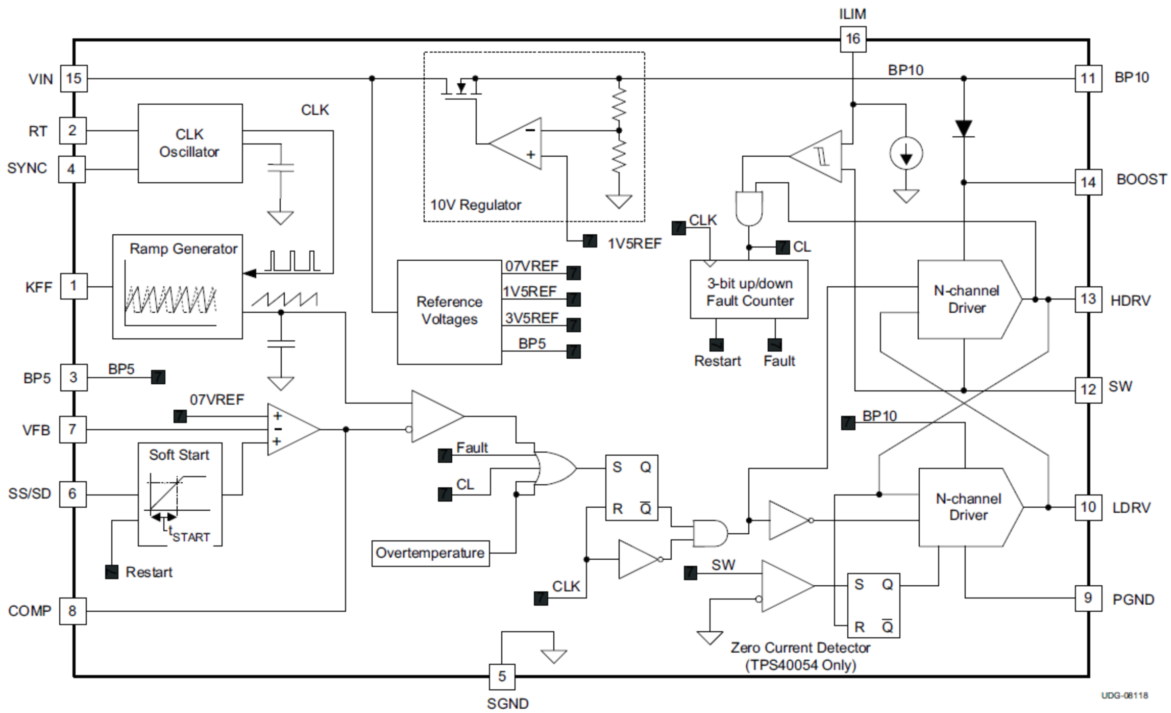

Figure 7-TPS40055 Block Diagram[4]

The first two pins that should be identified are the input voltage VIN (pin 15) and signal ground SGND (5). These two pins are set to the battery supplied positive and negative terminals of the battery for supplying power. The next two most obvious functions are the HDRV (13) and LDRV(10) pins, which are directly connected to the P and RSWITCH MOSFETS which were discussed earlier in switching the output voltage.

The BP5 (3) and BP10 (11) are quite simply reference voltages that are created by the chip in order to supply the internal hardware with the power required for switching. In the application, these references are tied to high and low respectively through high value capacitors in order to prevent sharp changes in value while still isolating the steady state values for measurement for testing. The only other output ports are BOOST (14) and COMP (8). BOOST (14) is simply the monitor for the PSWITCH

[4] (Texas Instuments, 1995-2010)

controller. The COMP (8) pin along with connecting hardware sends an output from the error comparator in order to ensure both a soft startup as well as consistent operating conditions.

All other pins inside the TPS40055 chip require an input and determine the functionality of the circuit such as output voltage and current. The ILIM (16) and SW (12) pins both converge on a hysteresis comparator shown in the top right of Figure 7. ILIM (16) is set with a resistor and capacitor to set a boundary for current output. This value is compared to SW (12), connected to the MOSFETS in order to determine if the output current is too high compared to the set value from ILIM (16). It can be noticed that R25 in each converter circuit has a value of zero ohms to ensure that the SW (12) pin does not receive too much current, thus acting like a fuse.

In the lower left hand corner of Figure 7, pins VFB (7) and SS/SD (6) converge at the error comparator, determining if there is an error in the output signal. VFB (7) is applied directly to the comparator and should equal the reference voltage of 0.7 volts in order to allow the soft start mechanism to change the output as required. The SS/SD (6) pin is perhaps the most complex of all the pins within the converter circuits. The capacitor C4 in Figures 4, 5, and 6 are energized with current during startup, changing the value at SS/SD (6) as more time elapses. As the energy within the capacitor is discharged, the logic circuitry changes the driver frequency in order to allow for a gradual increase in output voltage as opposed to the sharp and potentially unstable rise without the soft start.

The pins RT (2) and SYNC (4) both control the clock oscillator. The resistor R4 in the converter schematics sets the switching frequency for pin RT (2) while the SYNC (4) pin is connected to VIN because there is no other frequency that is being used in our application. For different applications, SYNC (4) would be connected to a master clock in order to keep the circuit synchronized with other actions.

The final two pins, KFF (1) and PGND (9), have two completely different purposes. KFF (1) controls the slope of the ramp signal used for internal processing by the connection of R7 to VIN. PGND (9) on the other hand controls the lower MOSFET operation. Because all of the modulation due to over current and errors is done on the upper MOSFET this pin is connected directly to ground in order to maintain a steady output signal.

While some of the component values amongst the three converters vary, the general design is maintained. The different values simply select the different output voltages, currents, and qualities that were required for the three different circuits contained.

Design Analysis

The design tool was able to quickly calculate the expected characteristics of the converters. The converters all had output voltage ripples below 25 mV, and an on time less than 3 microseconds. This will of course have to be tested in the final product to ensure the design is achieving its goals. Overall, there are no expected issues in the regulation of this design.

It is also expected for all designs to have greater than 90% efficiency in standard operation but this will also need to be verified. This efficiency is excellent and should far exceed the commercially available product. A table of all expected values of the design can be found in Appendix D of this report.

Thermal Consideration

Using the Switcher Pro design tool from Texas Instruments the program was able to tell us the components that contained the most current and thermal liability. Of each of the three circuits, the only current bearing components are Q1, Q2, and L1. Due to the nature of inductors, the temperature of the inductor is not a factor. Looking at peak conditions for each of the other components, we calculated the following temperatures:

Circuit	Component	Estimated Temp at Max Load (^{o}C)
24-12	Q1	105
24-12	Q2	50
24-3.3	Q1	94
24-3.3	Q2	120
24-5	Q1	119
24-5	Q2	123

Table 2-Calculated Thermal Components

These calculated temperatures are incredibly important due to the estimated temperatures these components could operate under. Despite these values, the group decided that the thermal pads being created beneath the chips would transfer the heat created away from the chip and into a thermal layer created inside the board, acting like a giant heat sink. Because the size of the thermal layer, individual heat sinks should not be required.

In addition to the thermal layer, the enclosed structure will contain a fan controlled by a thermal sensor. If the enclosure reaches a specified temperature, the fan will activate and circulate air for additional cooling.

Fan Circuit Design

This power supply will require cooling when operating in the higher load regions. To increase efficiency it is preferable that the cooling only operate when needed and not continuously running. To achieve this, a simple circuit has been created using a thermal sensing part and a P channel MOSFET. The AD6502 is a small thermal sensing device with hysteresis that is factory designed for a certain temperature based off ordering code. When this temperature is reached the voltage on the output then drops from logic high to logic low at a level of 5 volts to 0 volts. The technology used is an open drain transistor so this device requires a pull up on the output to operate correctly.

Phase Gain Analysis

The circuitry of the TPS40055 is very good but it requires additional components in order to compensate the error amplifier to be stable. This is achieved by correcting poles and zeros in the frequency domain in order to have the correct roll off and filter out high frequency signals in order to maintain a steady output with no spikes or instability. The following graphs are a representation of the phase and gain of the error amplifier. It should be noted that the simulation and design tool utilized allowed for a rapid selection of values for these parts and even though the gain plot is not perfect it is good enough for proper stable operation.

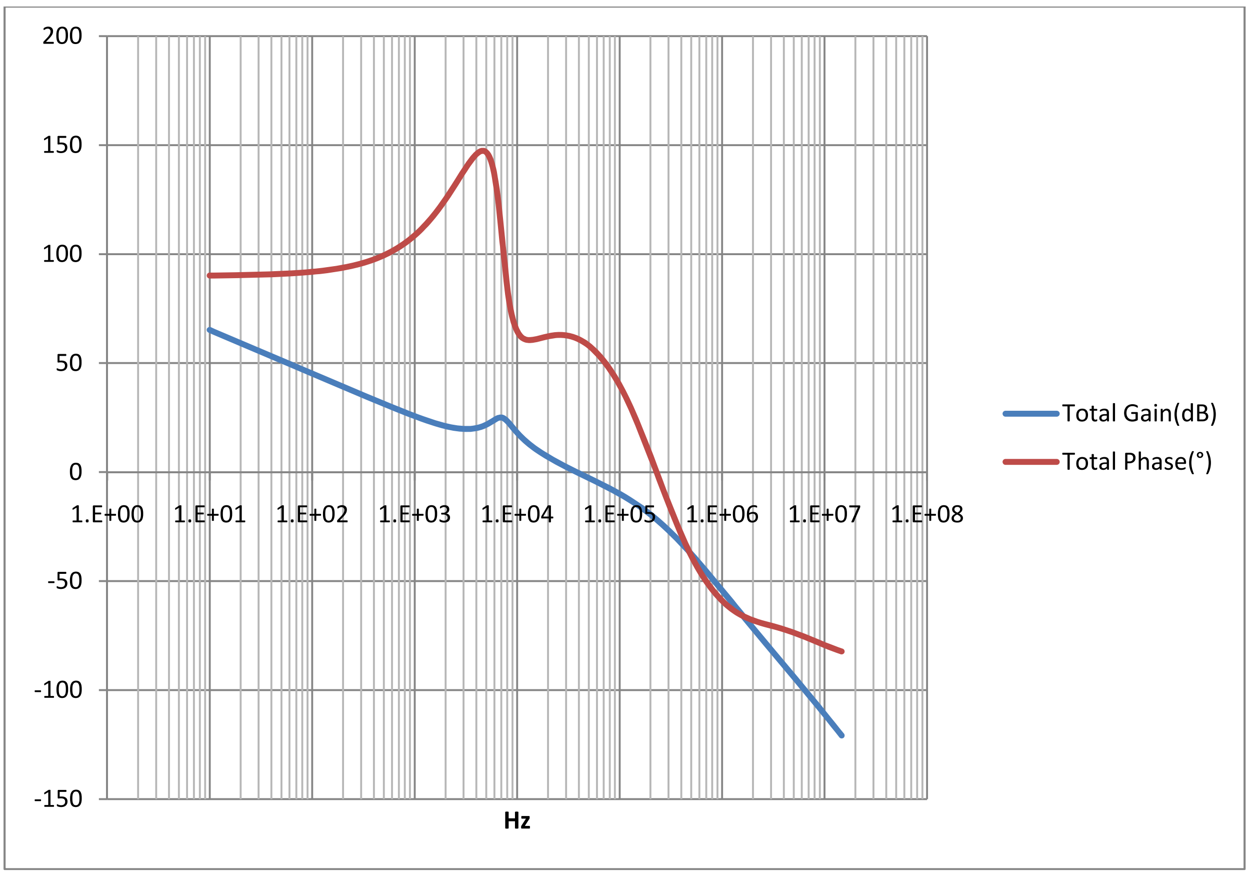

Figure 8-12 Volt Rail Phase and Gain Plot

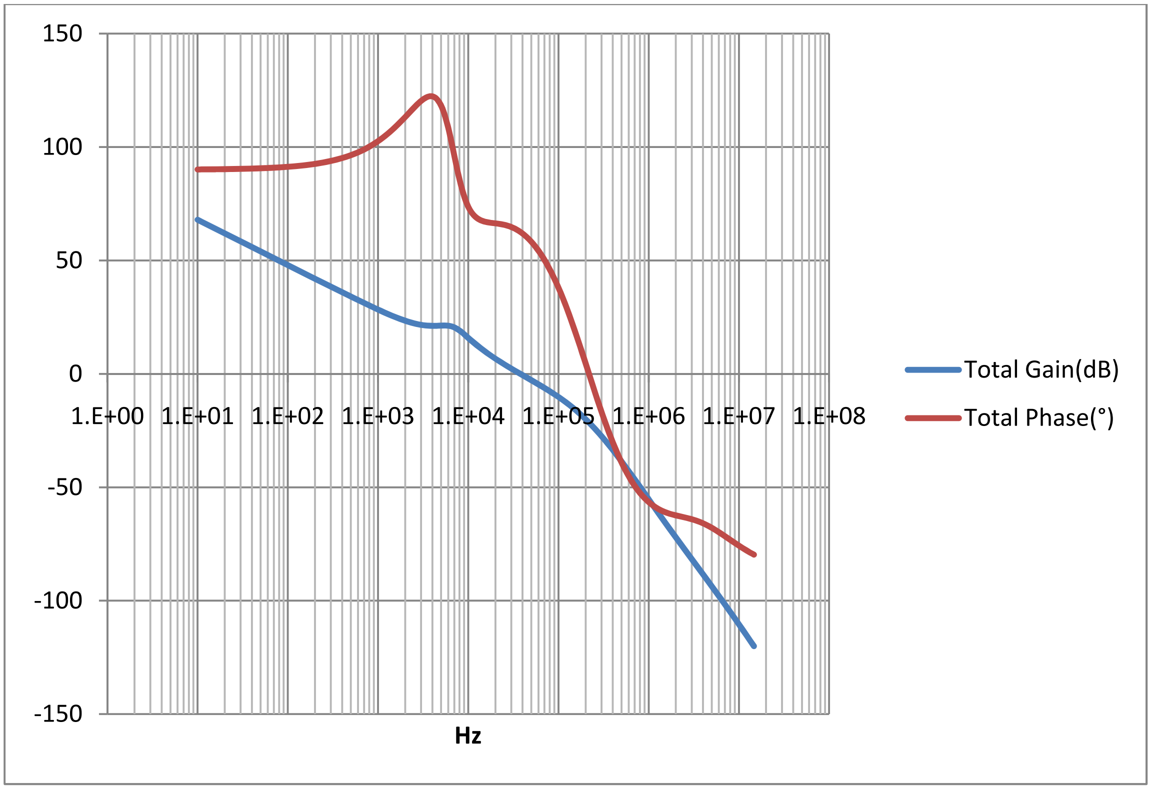

Figure 9-5 Volt Rail Phase and Gain Plot

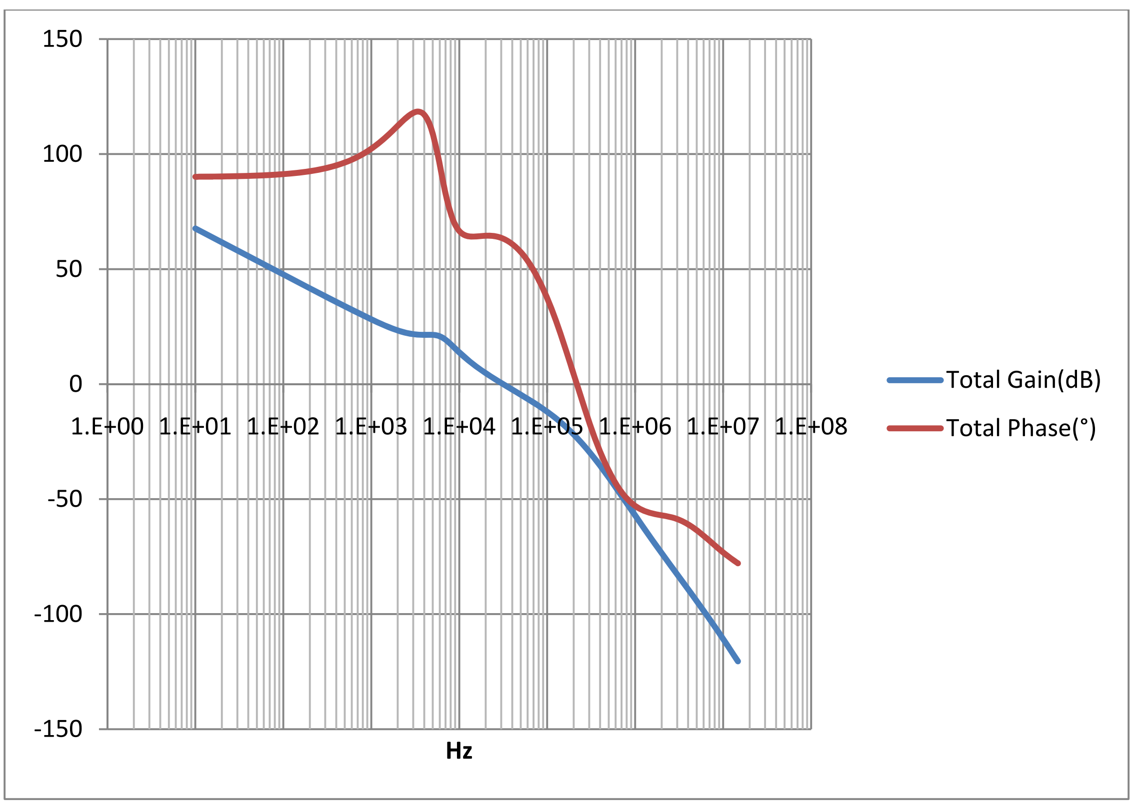

Figure 10-3.3 Volt Rail Phase and Gain Plot

Circuit Implementation

The system will be implemented utilizing surface mount devices on a four-layer printed circuit board. A printed circuit board is a fiberglass substrate with traces of copper that connect the necessary pins of all components. The printed circuit board for this device will be four layers. Many different goals were kept in mind when designing these printed circuit boards, as they were required to be hand assembled, easy to work on, dissipate the heat generated by the circuitry, as well as being a standard size. The size chosen for the circuit boards was the base size of a standard ATX power supply.

Some compromises occurred to balance the size of the design with the easiness to rework the board as needed. This came down to going from a two-layer board to a four-layer board. This made rework more challenging because some traces are not available to work with as they are contained within the board. In the end, though it made layout considerably easier as well as added more copper for dissipation of heat. Only a few traces needed to be moved into the core of the board and these were limited to signal traces and were left in such a way that they could be rerouted if necessary.

The top layer contains the majority of signal traces as well as a large amount of copper power planes to help reduce noise and increase thermal dissipation. This layer will be the layer on which the components are soldered upon.

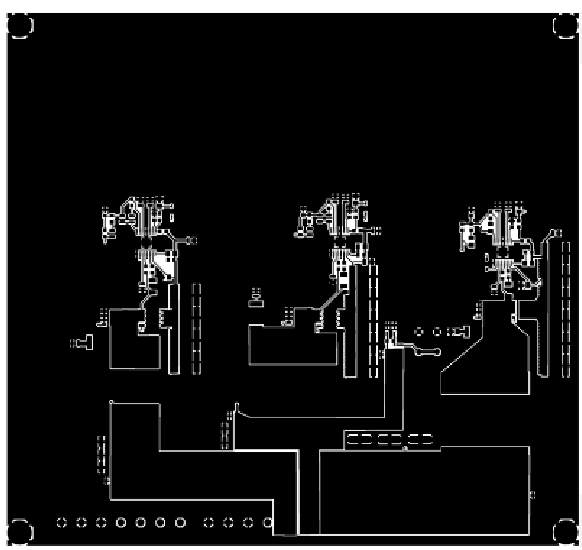

Figure 11 - PCB Copper Top

The first inner layer contains power planes to transmit power as well as ground plains to have even copper distribution. There are some signal planes that have been run due to a lack of room on the top copper layer.

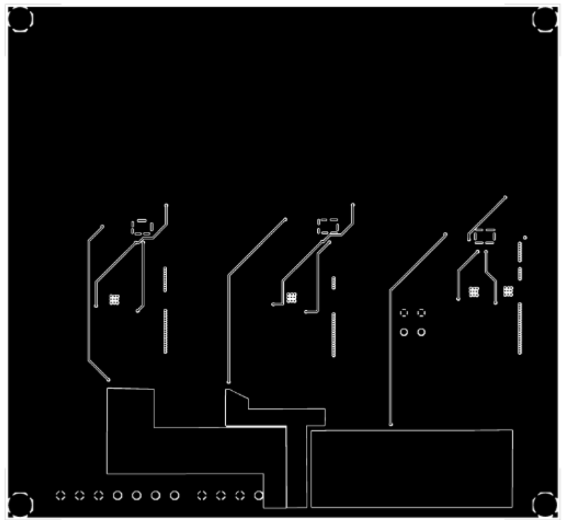

Figure 12 - PCB Inner 1

The second layer contains only planes and is used for current carrying for power outputs and extra thermal dissipation. This is a very simple layer and is used to not only reduce thermal issues but to also reduce the amount of warping that occurs in the printed circuit assembly.

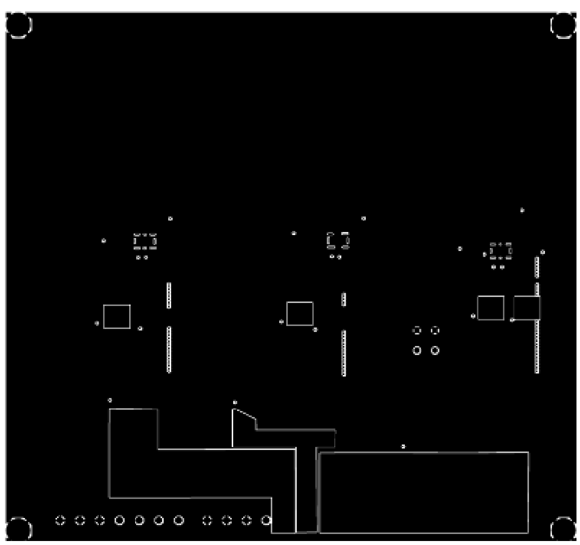

Figure 13 - PCB Inner 2

The bottom copper layer is the main distribution of the 24 volt input to the power supply circuits. This was made to be a full plane to reduce resistance as well as dissipate heat from the devices. There are also current carrying planes for the output voltage on this layer.

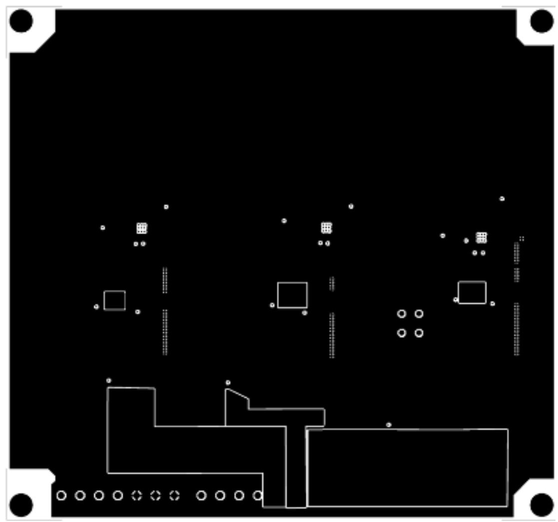

Figure 14 - PCB Copper Bottom

The silk screen layer is used to assemble the board as it defines all parts on the board by their reference designators. Without this assembly would be an excessively difficult and time consuming task as it would require constant reference to the schematics.

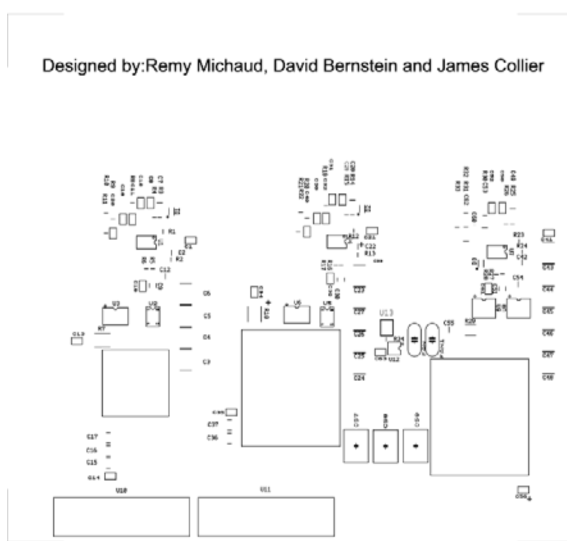

Figure 15 - PCB Silkscreen

The printed circuit board utilizes a two-ounce copper finish; this refers to two ounces of copper per square foot or .0028 inches of copper. This increased copper thickness will allow for a greater amount of heat dissipation but as a side effect will make soldering the parts to the board a more challenging task. The increased difficulty from this can be overcome by preheating the solder surface before soldering the part down.

Surface mount technology allowed the design to be kept to a footprint comparable to the ATX power supply and kept all components on a single side of the board for easy rework. Because of the surface mount components, the final finish chosen was ENIG or Electro-less Nickel Immersion Gold. This finish is particularly smooth lending itself well to surface mount soldering and has good oxidation resistance. This process involves the board being immersed in a nickel solution to provide a good solder surface and then finished with a flash plate of gold to prevent oxidation. It is currently popular in industry as a finish for most printed circuit boards.

Mechanical

Final dimensions of the power supply have been set at 6” deep by 5.5” wide by 3.5” high. There are the standard dimensions for an ATX power supply which was chosen for its ability to easily fit our circuit and cooling inside as well as being the same footprint as what is currently being used in the Prometheus robot. The supply will feature two screw terminal blocks, on the same side of the case, to leave other sides open for cooling or to allow them to be placed against other components. One terminal block will feature two circuits and will be for supplying input power to all of the DC-to-DC converting circuits. The other terminal block will have six circuits and will be for the outputs for all three DC-to-DC converting circuits. Screw terminal blocks were chosen for their ease of use, flexibility and durability. Inputs and outputs will be clearly labeled on the power supply case near the corresponding terminal block circuits.

Heat will be kept in check by both passive and active coolers. Components that generate the most heat, such as the switching MOSFETS and the switcher controllers, will have copper or aluminum heat sinks attached to help keep temperatures in check without using any extra power. If ambient temperatures get high or under particularly heavy loads, the active cooling system will kick in. This system will consist of two smaller fans to the side of the circuit board that will draw cool air into the case through openings, across the hot components, and then exhaust the heated air through the side of the case. The fans will power on when a temperature switch located under the heat sinks passes a certain threshold. By only turning on active cooling when it is needed the most, the overall efficiency of the DC-to-DC power converter should not be significantly impacted. An artist's rendering of a possible case design can be seen in Figure 16 on bellow.

Figure 16 - Artist's Rendition of Possible Case Design

III – Production and Test Planning

All new products must follow a production and development schedule to stay on track the proposed production and test-planning schedule for the Modular DC-DC Power Converter for Robotic Applications can be seen in the Gantt chart below.

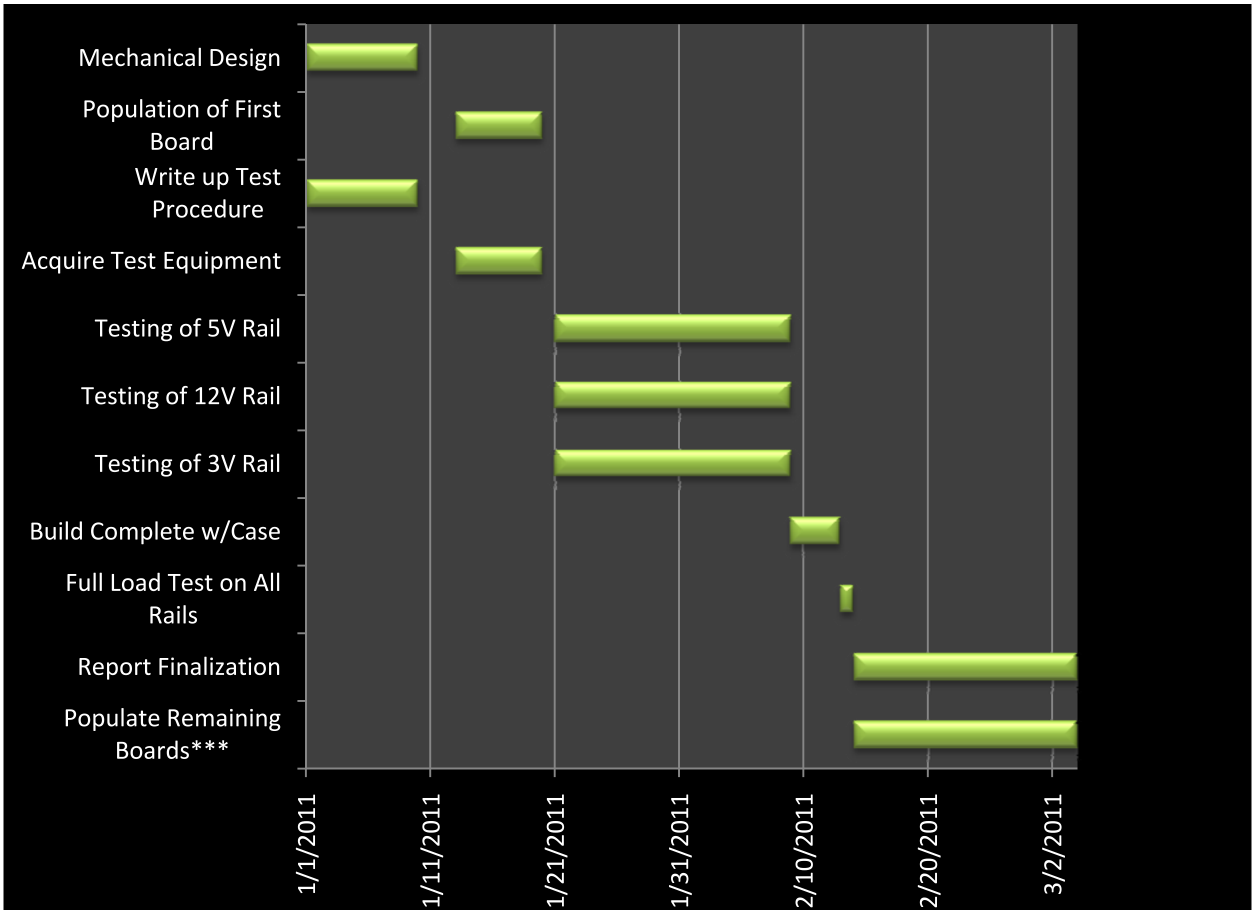

Figure 17 - Production and Testing Gantt Chart

The time leading up to the start of C-Term will be used to produce a final mechanical design for the power converter's case as well as procurement of the materials required for the case's assembly. This time will also be utilized for development of procedures with which to test each separate DC-DC converter circuit, as well as a procedure for testing all circuits at full load.

The first week for C-Term has been set aside for population of the first PCB. Part placement and soldering will be the responsibility of all three project members. This week will also be used to acquire or locate all equipment needed for functionality and load testing. Once the board has been populated, the next 19 days have been set aside for testing proper functionality of the DC-DC converter circuits as well as making any slight adjustments.

Once the testing period is complete, the next five days will be for assembling the power converter completely with its case. This allows for built in time to test the functionality of the active cooling circuit. Once final assembly is complete, a full load test will be done on all rails.

Following this timetable, a fully functional DC-DC power converter should be assembled and tested by 2/14/2010. This should allow adequate time to finalize the MQP report as well as the possibility of populating the remaining boards.

Assembly Process

The high current abilities of this supply can provide thermal problems with the MOSFETS used. The board that was designed contains thermal reliefs beneath many of these components to allow for as much heat dissipation as possible. The four copper layers provide enough heat dissipation to cool these components but can make assembly very difficult.

No matter if one or all three circuits are being assembled, each circuit should be assembled in the same manner. The first components that should be assembled are the inductors. Due to the large footprint, the inductors require the most heat to attach than any other part. Apply solder to both the board contacts and the component contacts separately, place the inductor lined up as well as possible, and use a heat gun to melt both deposits of solder to each other. Make any last alignment changes as required and allow to cool. If enough heat has been applied, the inductor should lie flat with against the board and be firmly connected. Additional solder can be added with a soldering iron if desired.

Similar to the inductor, the MOSFETs and switcher IC chips should be applied in the same manner; applying solder to each contact then using the heat gun. Special caution should be taken when applying these components, as alignment is of vital importance. If the chip is misaligned or contains too much solder, solder connections can be made to unwanted contacts, resulting in improper functionality.

All other resistors and capacitors can be attached with normal soldering iron attachment techniques after the chips have been placed. It is important to apply the inductors and chips first to avoid any accidental realignment that may occur when using the heat gun.

IV - Results

After the design was completed and assembled two circuit boards were available for testing. One circuit contained the 5 and 3.3 rails as the 12 volt rail was inoperable after a failed assembly check. The newer board contains the 12 volt rail and had a much cleaner assembly. The following pictures are first, the original board with 5 and 3.3 volt rails, followed by the new board which has the 12 volt rail.

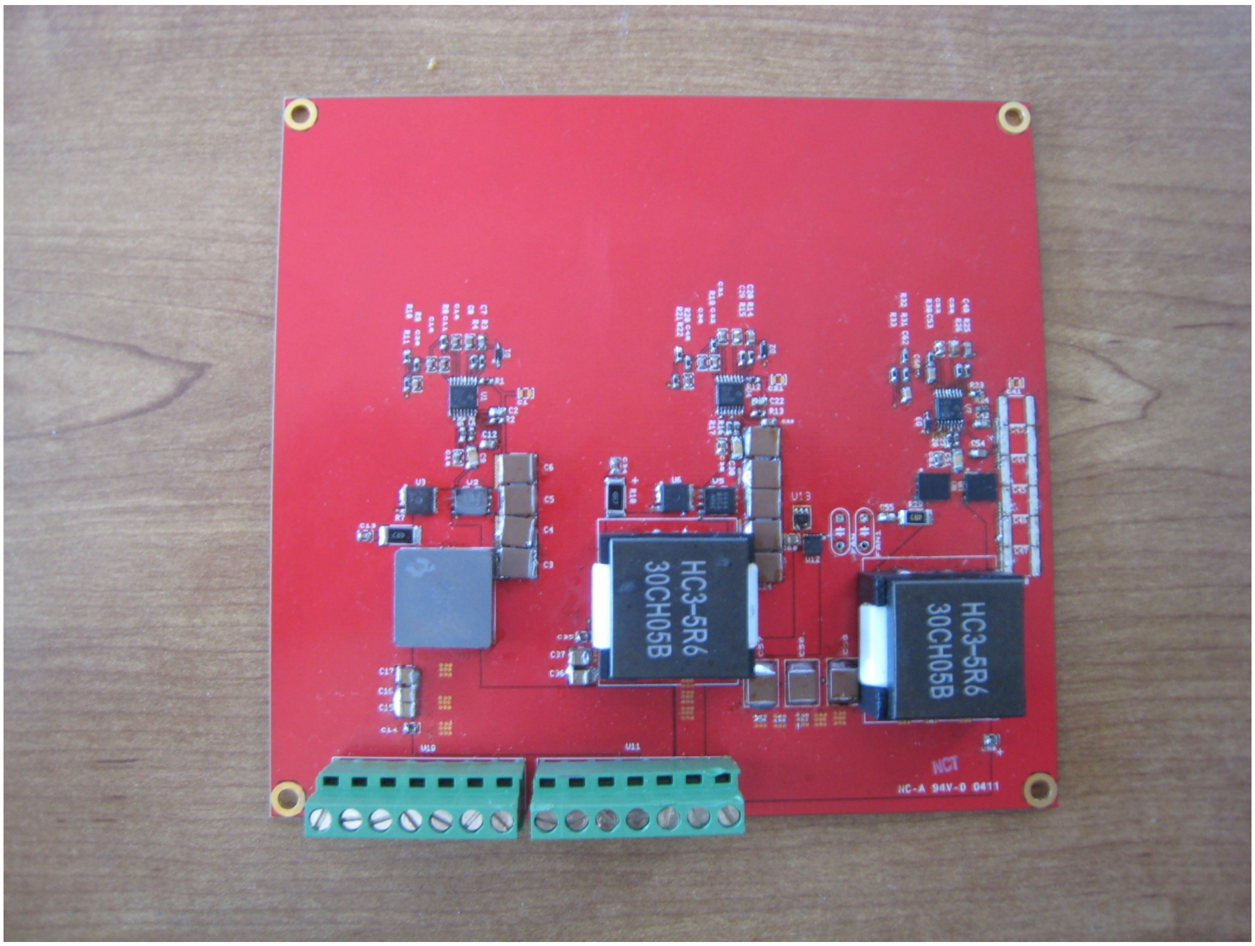

Figure 18-5 and 3.3 Volt Rail Assembly

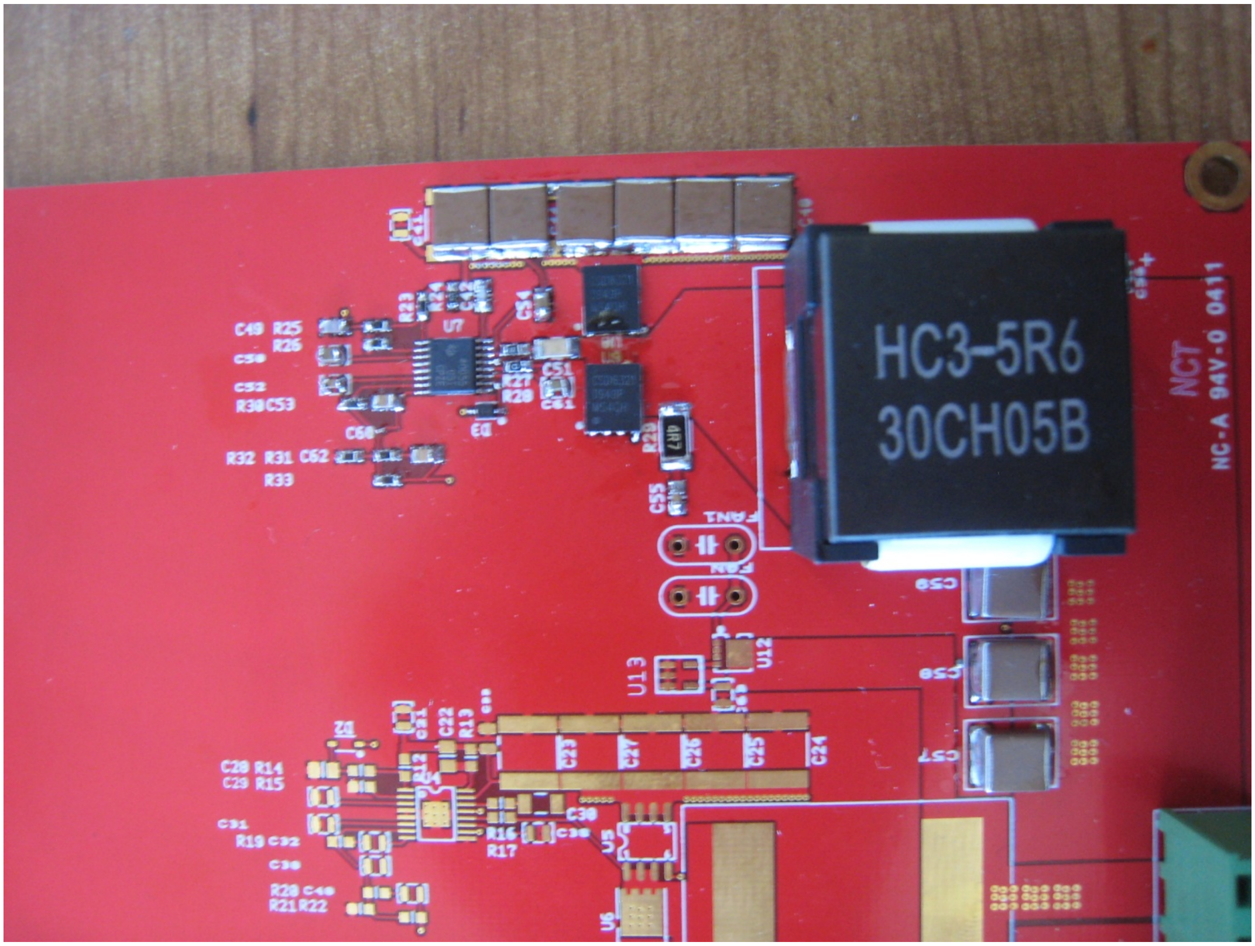

Figure 19-12 Volt Rail Assembly

To test the designed circuit and layout proved to be a surprisingly difficult task. A full test of the supply would require small loads for high current testing as well as a high current power supply. Initially, the board was connected to a simple DC bench-top power supply to allow for up to a 3A draw. After testing as much as possible, the supply could be switched out for two car batteries in series to create the desired 24V input. Using car batteries would allow for as much current as needed to test the higher current loads.

The open load test was the first and easiest, as it required no connection to the output terminals. To test the lower current draws, a resistor bank was added. This bank allowed for the slow addition of parallel resistors, which allowed for small quantities of current to be added or removed for specific test values. The resistor bank did not provide a small enough resistor to test the larger current draws. In order to lower the resistance even further, 100 and 55W car light bulbs were added in parallel to the banks. Between the light bulbs and resistor banks, a sufficient load was placed on each circuit to adequate testing. These light bulbs were more of a dynamic load than would have been wanted for this test as they had an extremely low resistance while cold causing a current surge that required sequential illumination of the bulbs for safety.

The screenshots found in Appendix E display the input and output voltages measured for the board. Connections were made at the leads connected to the board so that no line loss would be measured. The blue probe was connected to the output being tested while the yellow probe was connected to the input.

Ammeters were used at both the input and output connections to monitor the amount of current being drawn. The readings measured on each ammeter were the current values recorded for all data presented. The data is found in the tables that follow. Some tests were not exactly as planned and those are noted by having the actual load used in the data.

The oscilloscope screenshots found in Appendix E show the transient responses corresponding to each of the table values presented. As an example the 5 amp tests will be shown here and explained. The rest of the test data can be found in the following but the screenshots that this data was taken from are found in Appendix E in their entirety. The data was calculated based off of standard 10 to 90 rise times, and 90 to 10 fall times. The data for settled values were after all transient value had ceased once the supply had been power on. The peak values were taken at the peak point of the rise in voltage from power on. This data has been collected together for ease of viewing the tables that follow the scope shots.

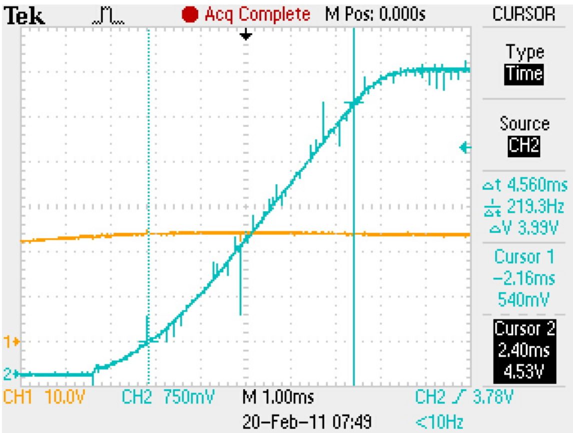

Figure 20-4.87A Load, 5V Rise Time

Figure 20 to the left shows the rise time transient using the cursor feature on the oscilloscope. The cursors are placed at the 10% and 90% of maximum values. The Δt value to on the right side shows the amount of time it takes to change the signal from 10% to 90% of maximum. The rise time was measured to be 4.56 ms

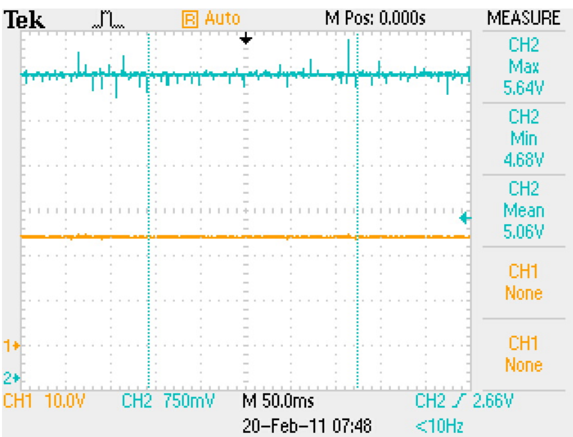

Figure 21-4.87A Load, 5V Peak and Settled Values

Figure 21 to the left displays the 5 amp load for the 5V rail. The oscilloscope's measure feature was used to take the maximum, minimum, and mean values of the output signal (blue). The input value (yellow) was measured simply to ensure that no abnormal behavior occurs to the input supply. The supply does not actually change as rapidly as displayed, but the maximum and mean values of 5.64V and 5.06V are good enough for the data.

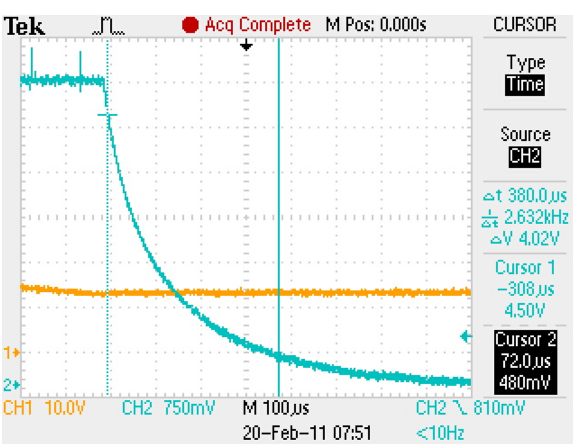

Figure 22-4.87A Load, 5V Fall Time

Figure 22 displays the 90% to 10% fall time in the 5V rail under 5A load. The fall time was measured with the cursor function to be 380µs.

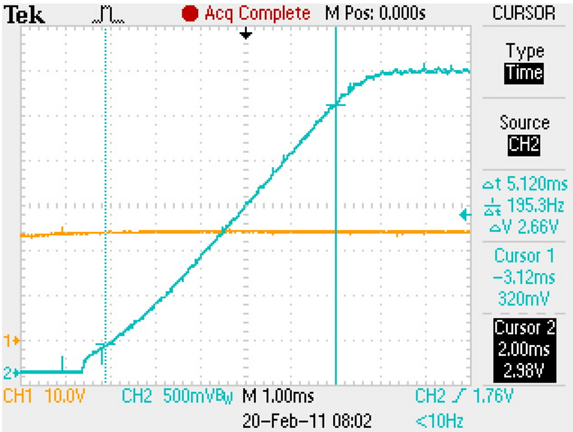

Figure 23-4.46A Load, 3.3V Rise Time

Figure 23 shows the rise time transient behavior of the 3.3 Volt rail. The blue trace is the trace of note as this is the output. The yellow trace is again the input. The rise time was measured with cursors to be 5.12 ms.

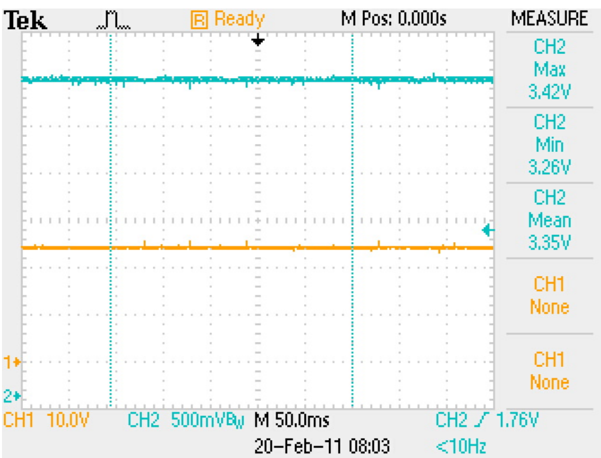

Figure 24-4.46A Load, 3.3V Peak and Settled Values

Figure 24 shows the settled values for the 3.3 volt rail at a 5 Amp load. Blue is the output and yellow is again the input. There are no notable oscillations beyond the noise of the measurement.

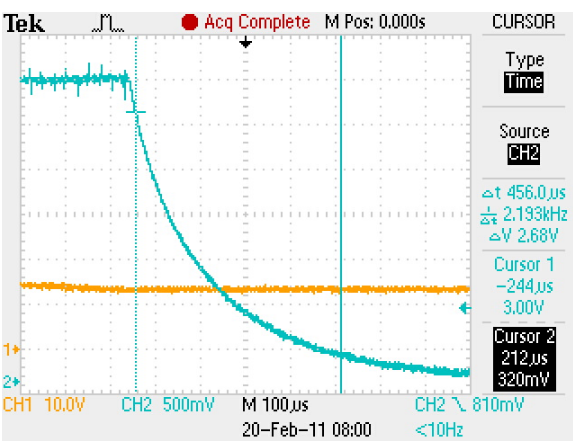

Figure 25-4.46A Load, 3.3V Fall Time

Figure 25 shows the same fall time measurement that was taken in Figure 15, only for the 3.3V rail. The cursors were used to measure a fall time of 456 µs.

Figure 26 shows the rise time of the 12 volt circuit with a 5 amp load. This was completed in the same way as the previous tests. The measured value for rise time is 5.04 ms.

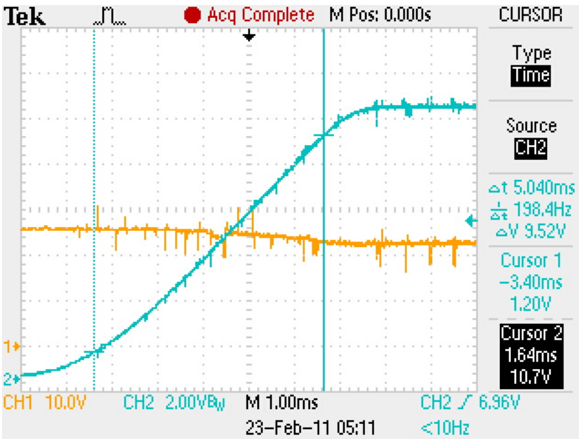

Figure 26-5.07A Load, 12V Rise Time

Figure 27 is the settled behavior of the 12 volt output at a 5 amp load. This follows the same measuring methodology previously stated. The settled value was found to be 12.1 volts.

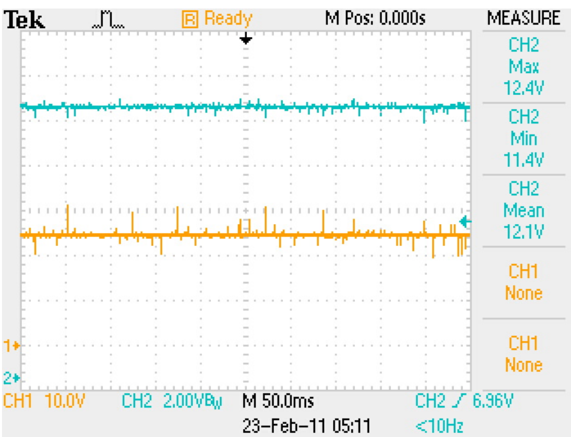

Figure 27-5.07A Load, 12V Peak and Settled Values

Figure 28 is the fall time of the 12 volt circuit under a 5 amp load. This is also the same measurement methodology of 90 to 10. The measured time was 900 µs

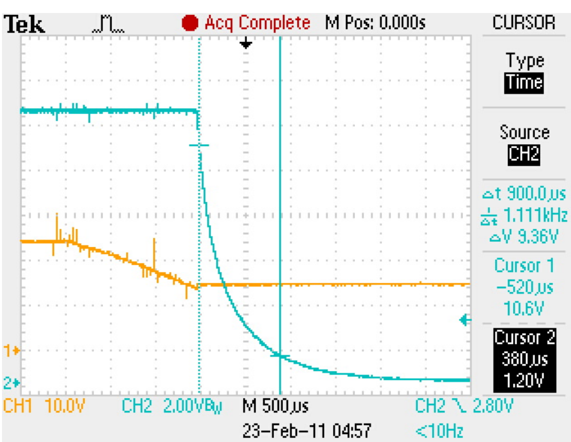

Figure 28-5.071A Load, 12 Volt Fall Time

Open	3.3V	5V	12V
Rise Time 90/10	5.1ms	4.7ms	4.96ms
Fall Time 90/10	5.45s	3.68s	980ms
Peak Value	3.4V	5.12V	12.5V
Settled Value	3.36V	5.07V	12.2V

Table 3-Open Load Results

Table 3 to the left shows the compiled data for the entire open load testing that was completed. The oscilloscope shots for these tests can be found in the Appendix E.

1 Amp Load	3.3V	5V	12V
Rise Time 90/10	5.1ms	4.64ms	4.96ms
Fall Time 90/10	2.04ms	1.6ms	4.8ms
Peak Value	3.4V	5.11V	12.3V
Settled Value	3.36V	5.06V	12.1V
Actual Load	1.02A	1.06A	0.98A

Table 4- 1 Amp Load Results

The screenshots that were used to determine the values in Table 4 can be found in Appendix E. The addition of the actual load row was used to display the loads that were actually tested.

5 Amp Load	3.3V	5V	12V
Rise Time 90/10	5.12ms	4.56ms	5.04ms
Fall Time 90/10	456µs	380µs	900µs
Peak Value	3.42V	5.55V	12.4V
Settled Value	3.35V	5.06V	12.1V
Actual Load	4.46A	4.87A	5.07A

Table 5- 5 Amp Load Results

Most of the 5A loads were slightly lower than 5A because of load restrictions, but Appendix E contains the screenshots for the determined values seen in Table 5.

10 Amp Load	3.3V	5V	12V
Rise Time 90/10	No Test	4.68ms	5.04ms
Fall Time 90/10	No Test	166µs	45µs
Peak Value	No Test	5.2V	12.4V
Settled Value	No Test	5.05V	12.1V
Actual Load	No Test	10.00A	10.04A

Table 6- 10 Amp Load Results

The data for the 10A load test can be seen in Table 6 with corresponding screenshots in Appendix E. No 3.3V rail was tested because of load availability. No load could be created to test the circuit at that level.

High Load	3.3V	5V	12V
Rise Time 90/10	5.28ms	No Test	No Test
Fall Time 90/10	2.14µs	119µs	No Test
Peak Value	3.44V	5.22V	12.6V
Settled Value	3.33V	5.05V	12.0V
Actual Load	8.55A	11.86A	18.04A

Table 7-High Load Results

Table 7 displays the data from screenshots in Appendix E in which the largest load was tested. Because of overhead capacitance and multi-meter failure prevented rise times and the 12V fall time measurements.

Min. V For Turn On @ 1A Load	17.9V
Min V For Operation @ 1A Load	13.5V

Table 8-Minimum Input Voltage Test

The input voltage was lowered until the circuit could no longer perform and the input voltage was recorded in Table 8. Similarly, the lowest input voltage at which the system will start was recorded.

V – Analysis

Before the circuit was operational, some changes needed to be made to the original design. Some of these design changes were caused by errors; others were forced due to lack of components. The design of each converter was itself operational as it was designed electrically.

Required Modifications from Original Designs

Board Redesign

The printed circuit boards required rerun due to an error in the conversion from schematic capture to board layout tool. Due to this error, the first boards received had about half of the components using the wrong part footprints. This was corrected in the layout tool by specifying a new footprint for these parts. Because of this change, the feedback section of each power supply was made smaller and the inductors footprints were made considerably larger. Thanks to Nashua Circuits this problem only caused a week delay in the project, otherwise this could have ended the project immediately.

Fan Circuit Modification

Due to an oversight in the fan, control circuitry a pull up resistor was missed on the temperature control IC support components. This problem was simply remedied with the use of a single 168k Ohm resistor from the 5-volt supply to the output pin of the temperature monitor IC. This fixed the fan control circuit. Without this resistor, the output of the circuit was always low delivering power to the fans no matter what the current temperature was.

Alternate Inductor Used On 5 Volt Rail

The required inductor chosen for the 5-volt rail was unavailable so the inductor from the 12-volt rail was used instead. This caused no major difference in the operation of the circuit except for a small loss in excepted efficiency.

Case Design Tweaks

To make troubleshooting easier, the decision was made to make the case a two-piece, hinged sheet metal design. Two, 5V 40mm fans were mounted in the top of the enclosure, exhausting hot air from the case. Intake vents were place on the same side of the case as the input and output terminal blocks. This design only requires that two sides of the case be unobstructed, increasing the usability for placing the power converter in robotic platforms where free space is at a premium.

Unexpected Failures on 12 Volt Rail

There was an accidental incident during one of the tests that damaged the first test board. This was caused by over-voltage the power supply by the external power supply being set to 48 volts and not 24 volts. The 5 and 3.3 volt rails were repaired but the 12-volt rail did not work properly after this error and a new 12-volt rail had to be built up on a new board. This new power supply board then worked properly and was used for all 12-volt rail tests.

Oscilloscope Noise

Noise is visible on many of the oscilloscope data captures found in Appendix E. This noise was determined to not be ripple as ripple becomes apparent at higher operating currents. This oscilloscope noise could be reduced with a better oscilloscope as well as shortening the measurement-ground lead length. The results from the data are not adversely affected by this noise though.

Difficulties in Testing High Loads

There was a large challenge in getting the appropriate load to test the higher current capabilities of this supply. This was overcome by the use of multiple loads in parallel including, 100 Watt H-3 light bulbs, 55 Watt H-3 light bulbs and resistor load banks. This brought on another complication through the behavior of the light bulbs. The light bulbs start as an extremely low resistance load causing large instantaneous current draw so they were required to be brought up in series. This prevented measurements of rise times at higher load, but there was little change in rise time in any measurement so this should not be an issue.

A secondary issue that had to be overcome was the current limit of 6 amps on the bench top power supplies. This was overcome by utilizing the two car batteries in series that will be used to power the supply in the Prometheus Robot. Precautions were taken when doing this test though as there was no set current limit and severe damage could be done to the device. There was a current meter in series with the batteries to monitor input current as well as in series with the output load. This allowed constant monitoring of the current during the tests so it could be aborted.

At one point, the digital multi-meter fuse was blown at 9 amps. The cause of this was not known as the multi-meter is rated at a current of 12 amps for the scale that was utilized. This required the removal of the multi-meter for the final current test on the 12-volt rail at a current of 18.04 amps.

Error in Voltage Levels

There was a small amount of error in the observed voltage levels. This is likely due to the tolerance of the components in the feedback network as well as the accuracy of the .7 volt reference inside the switcher control integrated circuit. The error was not that great though and does not pose any real issue in the use of the power supply. Improvement could definitely be made in this respect.

Efficiency Calculations

The efficiency of the power supply was calculated based off the data collected. It should be noted that since this power supply was designed to run at high currents its peak efficiency is at the higher currents and has a rather poor efficiency when running lightly loaded. This is due to the amount off current that is required to operate the switcher control chip compared to the amount of current that is delivered to the load. The calculations show that in the designed operation conditions, 98% efficiency is achieved. The efficiency of the 5-volt rail was adversely affected by the use of an alternate inductor and could be improved in the future. Overall, the efficiencies were quite impressive.

$$P_{In} = I_{In} * V_{in}$$

Equation 6-Power in Calculation

$$P_{Out} = I_{Out} * V_{out}$$

Equation 7-Power Out Calculation

$$Efficency = \frac{P_{Out}}{P_{In}}$$

Equation 8-Efficeny Calculation

12V @ 10A Efficiency	98.61%
5V @ 10A Efficiency	89.32%
5V @ 1A Efficiency	74.83%
3.3V @ 1A Efficiency	66.14%

Table 9-Efficencies of Power Supplies

VI – Recommendations

Though the power supply was operational not everything about the power supply was exactly as would have liked. A few changes could be made to improve the user friendliness of the device and provide some safety for the user. This would help increase the life span of the supply and prevent accidental damage to the device due to common accidents and unintended improper use.

Professional Assembly

The first major change that should be made if more of these are produced would to have them professionally assembled. The benefits of this would be reflowing providing a better contact on all thermal pads, better alignment on all parts from the pick and place machines as well as testing that would be completed by flying probe testing. This would take much of the debug work out of the system that is a result of hand assembly and is generally now standard on surface mount devices because of the size and difficulty of properly soldering thermal pads located on the bottom of parts.

Modification to allow independent powering of each supply

A second modification that would be extremely useful would be to separate the voltage inputs for each converter that way each converter may be tested independently. This would make debugging and design changes much easier and allow for isolation of faults for repairing the system. This would also be useful in allowing the user to deactivate the power supply rails that are not currently being used.

Power On Indication Light

A very useful addition to this product would be a simple LED with driver circuit to allow the user to know when the device is powered and when it is disabled. This would help avoid accidents with the power supply such as forgetting to power down the supply when changing the loads.

Reverse Voltage Protection

This would prevent powering the supply with incorrect polarity causing catastrophic damage if this was done by a non-current limited supply such as a battery. A simple to implement circuit would be to place a large diode that is rated for the correct current in series with the input voltage. This would prevent reverse voltage damage by going into reverse bias if the wrong voltage was applied stopping the majority of current flow.

Increased Accuracy of Power Supply

The power supply had some error that was observed. If this error is too great it could be decreased by using resistors with tighter tolerances in the feedback network. This would reduce the error by the same amount as the tolerances have changed. If this error is not great enough to be of concern for your application, the same resistors as used in these prototypes can be utilized.

Fused Input

When working on a non current limited input supply a simple fuse placed on the input voltage line would be a good precaution to take in the next revision. It would help prevent a catastrophic failure on the board as well as protecting the external power source such as a battery from overheating and or exploding. This fuse should be rated for at least 20 amps on the 24-volt input.

Case Design

Since the prototyping and testing stages are complete, the case design should be switched to a sealed case design. This will prevent extraneous dust and touching from possibly damaging the board. A sealed case design, like that used on ATX power supplies, is also more rigid and less costly to manufacture than a hinged case design like that used on this project.

Another possible change to case design could be the size. The ATX form factor followed in this project was chosen because it was the same footprint used in the current Prometheus ground vehicle. The PCB for this project could be easily downsized, allowing the width and depth dimensions of the case to shrink. The height could also be reduced as it will not affect the cooling system and the populated board height is less than 1.5 inches.

VII – Conclusion

This project was a great education experience. It required large amounts of research into the subject matter before design and construction could begin. The parts needed to be found and understood as well as the required layouts for these small surface mount components. The higher currents provided design challenge when it came to thermal considerations for the proper operation of the circuitry. The cooperation and guidance given to use by Nashua Circuits helped improve the printed circuit design to properly handle the higher current levels.

The physical building of this circuit was a challenging endeavor, as it required many innovative techniques to deal with the large amount of copper on the printed circuit board. The thermal pads on the parts required reflowing techniques that had to be imitated with the use of a heat gun instead of the standard reflow oven. This would not be feasible in any quantities other than a small prototype build.

The testing of the circuitry was truly a challenge as extremely low resistance loads were required at high power rating. Through a conjunction of resistive load banks and halogen lamps adequate tests were performed. This test gave a greater appreciation in how much power is really being used at these currents.

If this project is to continue into production, there are changes that should be made to this power supply. The hand assembly took a large amount of time and effort that could be reduced greatly by contracting an assembly house with the correct equipment. The power supply could also use its own fusing and power cutoff. Finally, now that the power supply is proven to work the case design can be modified to an easier to construct enclosure that does not have to be opened repeatedly.

This being said we believe the project to be a successful prototype as it was capable of meeting the design specification that was defined at the beginning of this project. There were many design related challenges and unexpected accidents that were overcome and in the end, the project was successful in what it planned to complete.

Appendix A – References

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Appendix B- Design Concept Questions

MF RBE DC-DC Power Converter

1. Size constraints:
    a. What basic footprint do we have to work with? (Height, Depth, Width)
    b. Do we have space/can we ask for space near each component for a modular system?
2. What Voltages will be required and at what currents will these be running at?
    a. Is there a system's diagram/flow chart that can be used to get an idea of the flow of power in the system?
    b. Do we need special considerations for any transients or inrush current requirements?
3. What monetary resources do we have to work with?
4. When would you like the working supply finished by?
5. What type of power source will we be regulating from?
6. Do we have to be able to charge the power source if given an external power source?
7. Are any frequencies off limits?
8. What environments will this robot be operating in?(Ambient Temperature Range, Air Tight, Water Tight?)
9. Do you need to know remaining battery life?
10. Do you need to know current draw from the battery?
11. Do you need voltage health monitors?
12. What connectors would you want on the power supply?

Appendix C- Schematics and Drawings

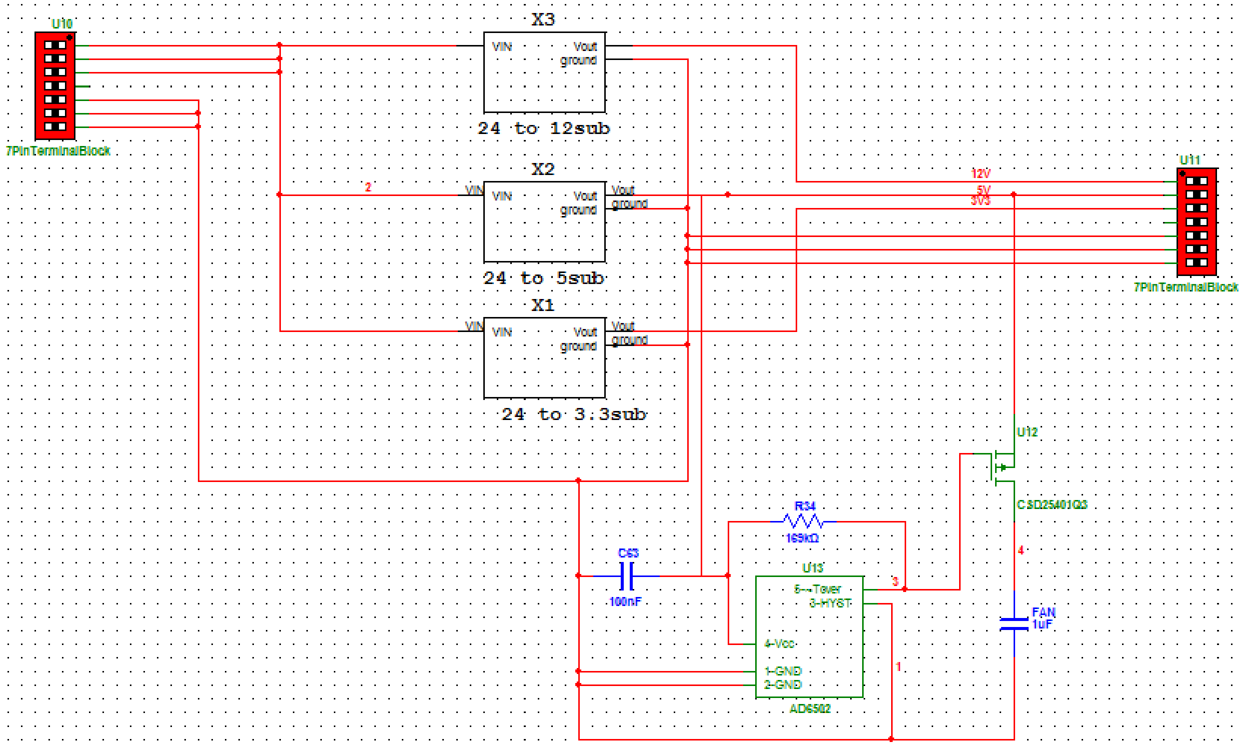

Figure 29 - Complete Electrical Schematic

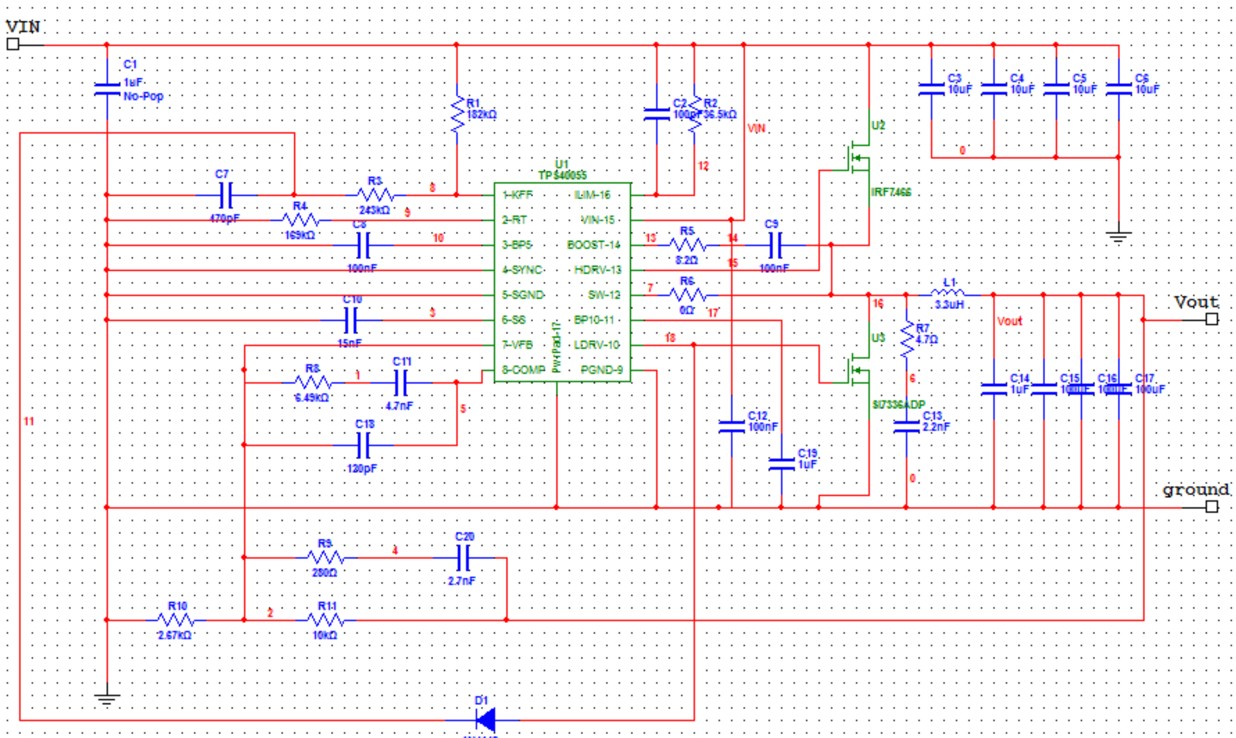

Figure 30 - 24V to 3.3V Converter

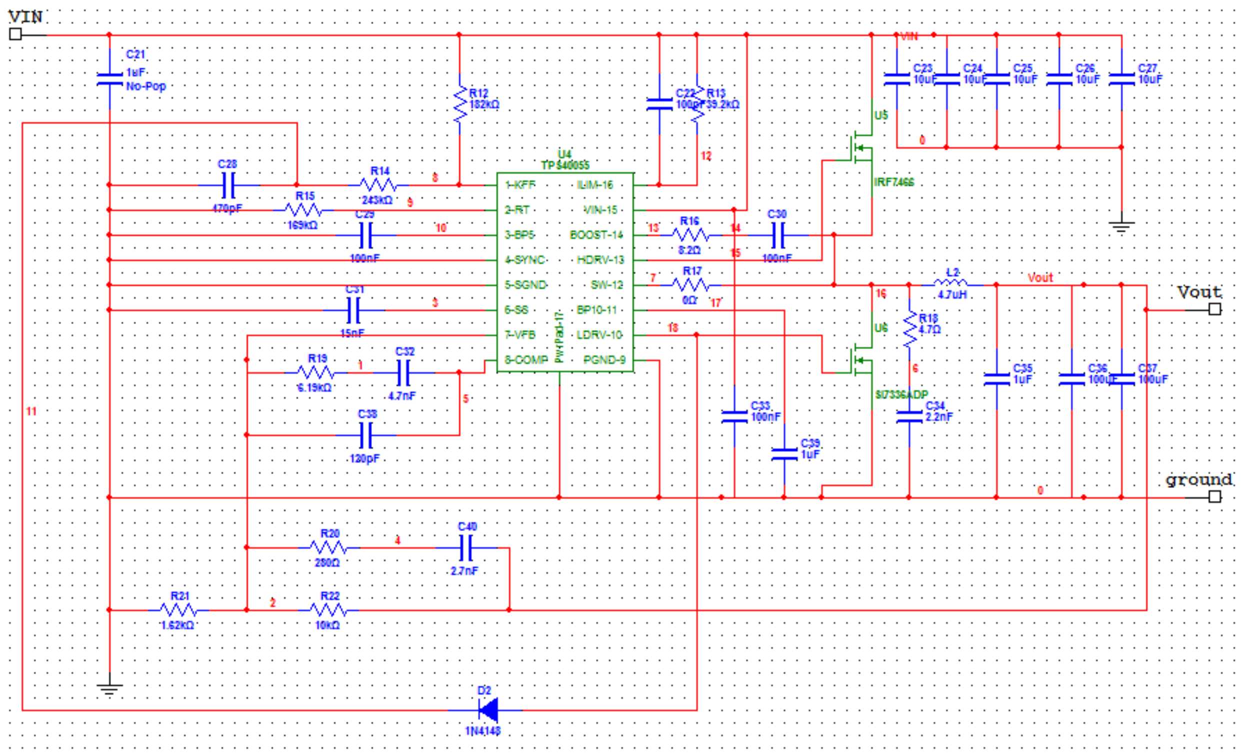

Figure 31 - 24V to 5V Converter

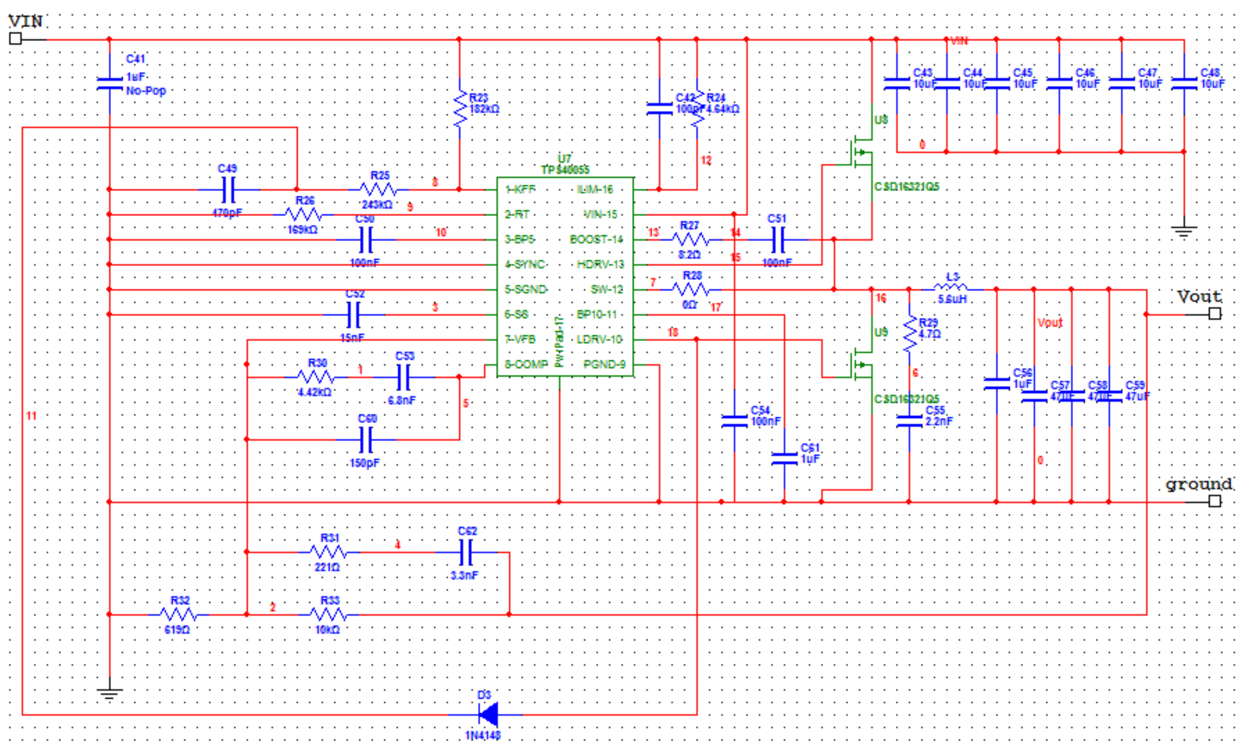

Figure 32 - 24V to 12V Converter

Appendix D- Tables, Graphs and Plots

Parameter	User Input Minimum	User Input Nominal	User Input Maximum	Default Input Minimum	Default Input Nominal	Default Input Maximum	Calculated Minimum	Calculated Nominal	Calculated Maximum	Units
Input Voltage	20	-	24	-	-	-	-	-	-	Volts
Input Ripple	-	-	-	-	-	480	-	-	343.7	mVp-p
UVLO(Start)	-	-	-	-	-	-	-	16	-	Volts
UVLO(Stop)	-	-	-	-	-	-	-	16	-	Volts
Switching Frequency	-	-	-	-	300	-	-	-	-	KHz
Slow Start	-	-	-	-	4	-	-	-	-	ms
Estimated PCB Area	-	-	-	-	-	-	-	2305	-	mm^2
Max Component Height	-	-	-	-	-	25	-	-	18	mm
Output Voltage	-	12	-	-	-	-	11.667	-	12.359	Volts
Output Ripple	-	-	-	-	-	240	-	-	21	mVp-p
Output Current	-	-	20	0.1	-	-	-	-	-	Amps
Inductor Peak to Peak Current	-	-	-	-	-	-	3.164	-	3.969	Amps
Current Limit Threshold	-	-	-	-	24	-	-	-	-	Amps
Gain Margin	-	-	-	-10	-	-	-	-22	-	dB
Phase Margin	-	-	-	60	-	-	-	61	-	Deg.
Upper FET RDSon	-	-	-	-	-	-	2	-	2	mOhms
Lower FET RDSon	-	-	-	-	-	-	2	-	2	mOhms
Duty Cycle	-	-	-	-	-	-	50.4	-	60.5	%
On Time Min(switch)	-	-	-	-	-	-	1526.6	-	2238.9	ns
Cross Over Frequency	-	-	-	-	-	-	-	38	-	KHz

Table 10 -24 to 12 Volt Converter Operational Analysis

Parameter	User Input Minimum	User Input Nominal	User Input Maximum	Default Input Minimum	Default Input Nominal	Default Input Maximum	Calculated Minimum	Calculated Nominal	Calculated Maximum	Units
Input Voltage	20	-	28	-	-	-	-	-	-	Volts
Input Ripple	-	-	-	-	-	560	-	-	325.5	mVp-p
UVLO(Start)	-	-	-	-	-	-	-	16	-	Volts
UVLO(Stop)	-	-	-	-	-	-	-	16	-	Volts
Switching Frequency	-	-	-	-	300	-	-	-	-	KHz
Slow Start	-	-	-	-	4	-	-	-	-	ms
Estimated PCB Area	-	-	-	-	-	-	-	2122	-	mm²
Max Component Height	-	-	-	-	-	25	-	-	18	mm
Output Voltage	-	5	-	-	-	-	4.886	-	5.159	Volts
Output Ripple	-	-	-	-	-	100	-	-	13	mVp-p
Output Current	-	-	20	0.1	-	-	-	-	-	Amps
Inductor Peak to Peak Current	-	-	-	-	-	-	3.031	-	3.32	Amps
Current Limit Threshold	-	-	-	-	24	-	-	-	-	Amps
Gain Margin	-	-	-	-10	-	-	-	-21	-	dB
Phase Margin	-	-	-	60	-	-	-	63	-	Deg.
Upper FET RDSon	-	-	-	-	-	-	13	-	13	mOhms
Lower FET RDSon	-	-	-	-	-	-	4	-	4	mOhms
Duty Cycle	-	-	-	-	-	-	18.4	-	25.8	%
On Time Min(switch)	-	-	-	-	-	-	558	-	957.4	ns
Cross Over Frequency	-	-	-	-	-	-	-	38	-	KHz

Table 11-24 to 5 Volt Converter Operational Analysis

Parameter	User Input Minimum	User Input Nominal	User Input Maximum	Default Input Minimum	Default Input Nominal	Default Input Maximum	Calculated Minimum	Calculated Nominal	Calculated Maximum	Units
Input Voltage	20	-	28	-	-	-	-	-	-	Volts
Input Ripple	-	-	-	-	-	560	-	-	317.4	mVp-p
UVLO(Start)	-	-	-	-	-	-	-	16	-	Volts
UVLO(Stop)	-	-	-	-	-	-	-	16	-	Volts
Switching Frequency	-	-	-	-	300	-	-	-	-	KHz
Slow Start	-	-	-	-	4	-	-	-	-	ms
Estimated PCB Area	-	-	-	-	-	-	-	1181	-	mm²
Max Component Height	-	-	-	-	-	25	-	-	7	mm
Output Voltage	-	3.3	-	-	-	-	3.237	-	3.408	Volts
Output Ripple	-	-	-	-	-	66	-	-	7	mVp-p
Output Current	-	-	20	0.1	-	-	-	-	-	Amps
Inductor Peak to Peak Current	-	-	-	-	-	-	3.221	-	3.404	Amps
Current Limit Threshold	-	-	-	-	24	-	-	-	-	Amps
Gain Margin	-	-	-	-10	-	-	-	-23	-	dB
Phase Margin	-	-	-	60	-	-	-	63	-	Deg.
Upper FET RDSon	-	-	-	-	-	-	12	-	12	mOhms
Lower FET RDSon	-	-	-	-	-	-	4	-	4	mOhms
Duty Cycle	-	-	-	-	-	-	12.3	-	17.3	%
On Time Min(switch)	-	-	-	-	-	-	374.2	-	641.8	ns
Cross Over Frequency	-	-	-	-	-	-	-	31	-	KHz

Table 12- 24 to 3.3 Volt Converter Operational Analysis

Appendix E-Images of Assembly and Testing Oscilloscope Captures

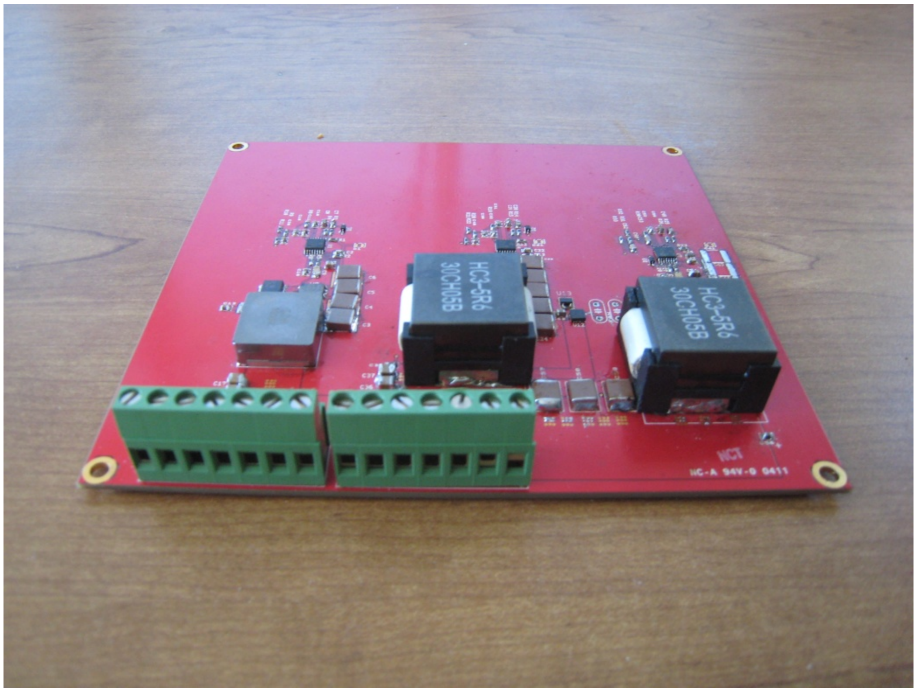

Figure 33-5 and 3.3 Front View

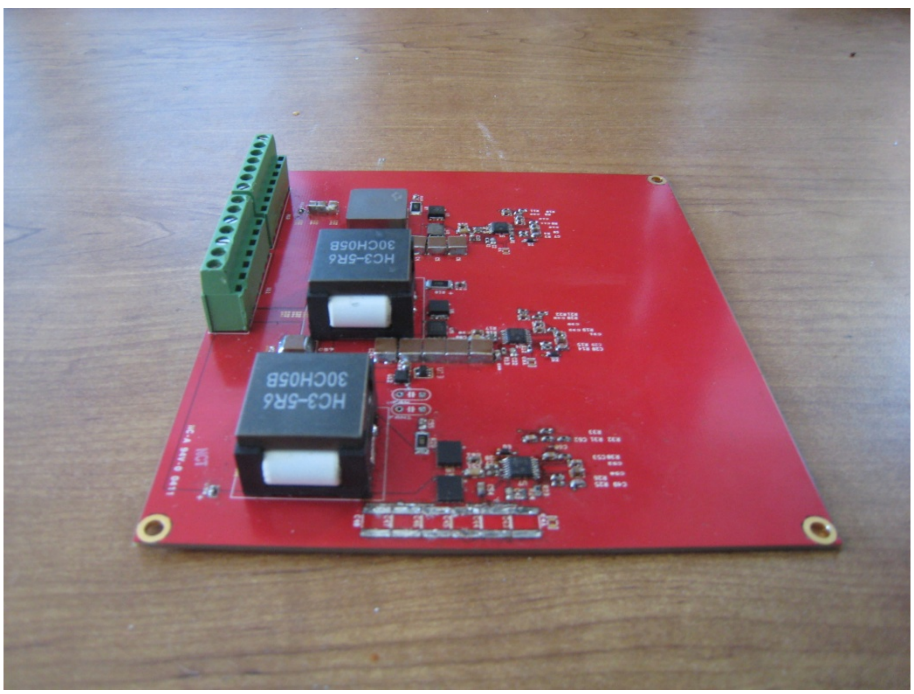

Figure 34-5 and 3.3 Right Side View

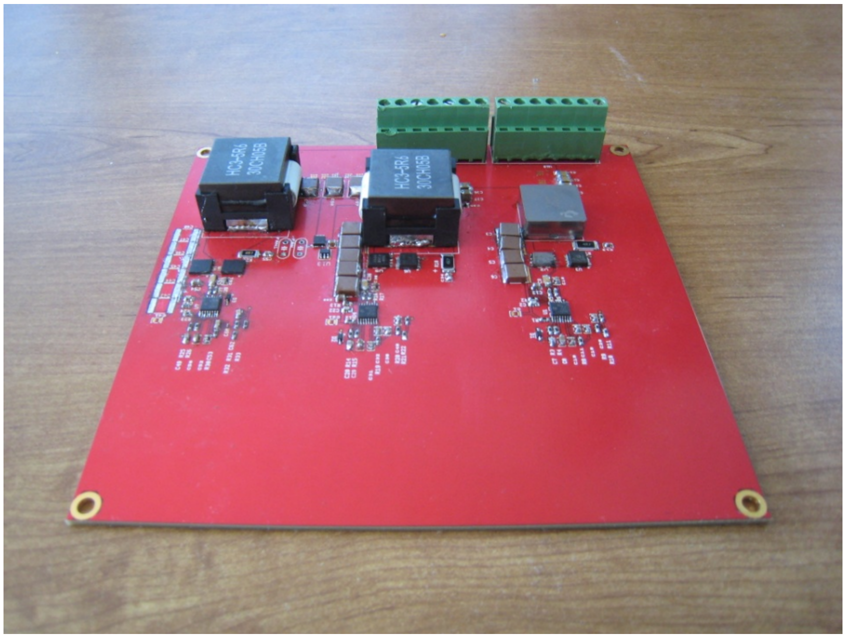

Figure 35-5 and 3.3 Rear View

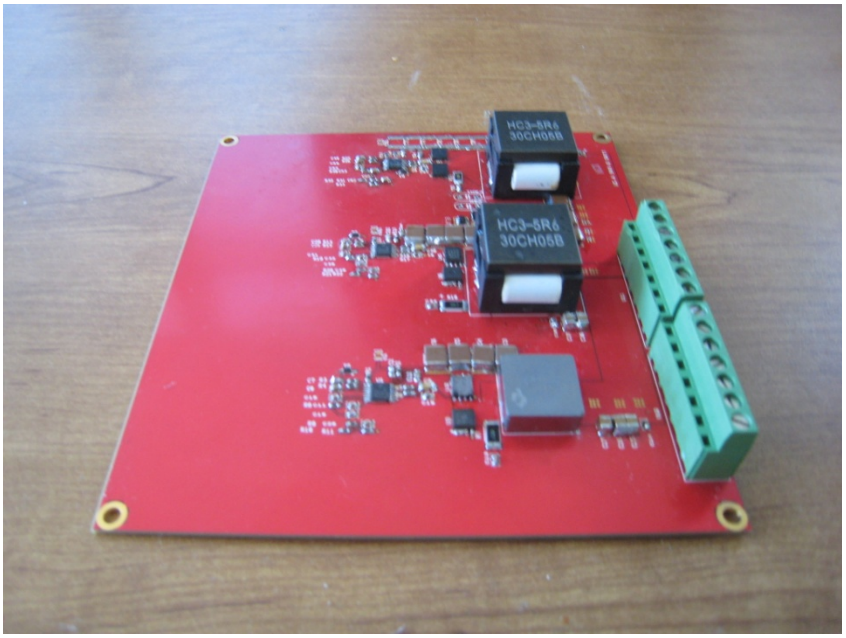

Figure 36-5 and 3.3 Left Side View

Figure 37-12 Volt Top Down View

Figure 38: Open Load, 3.3V Peak and Settled Values

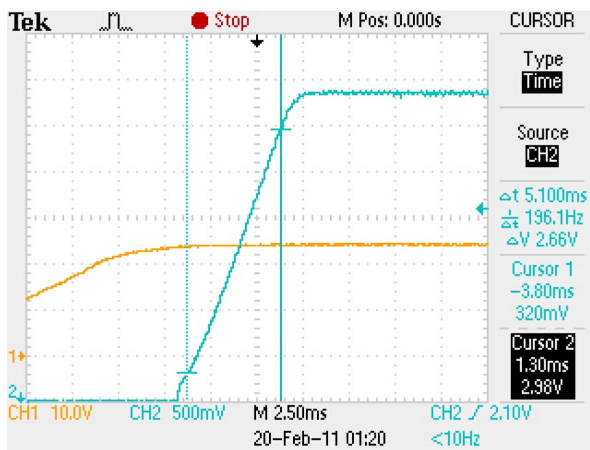

Figure 39-Open Load,, 3.3V Rise Time

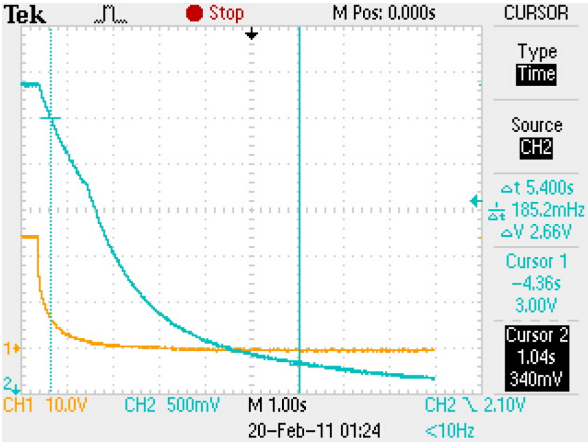

Figure 40-Open Load, 3.3V Fall Time

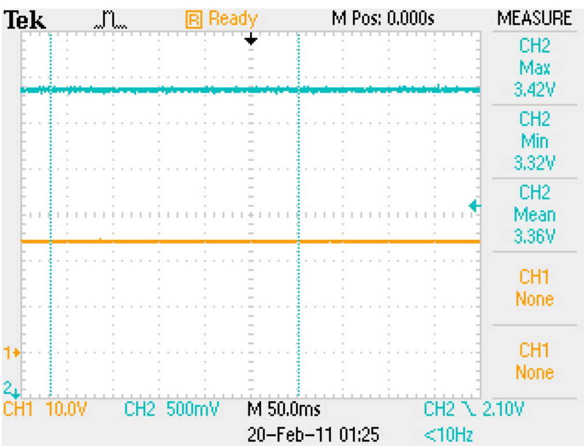

Figure 41-1.02A Load, 3.3V Peak and Settled Values

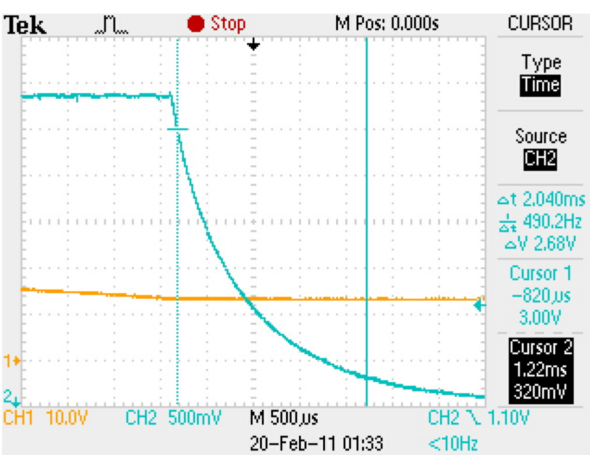

Figure 42-1.02A Load, 3.3V Fall Time

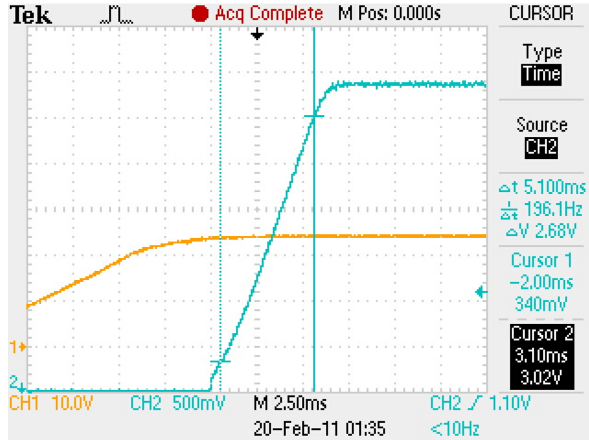

Figure 43-1.02A Load, 3.3V Rise Time

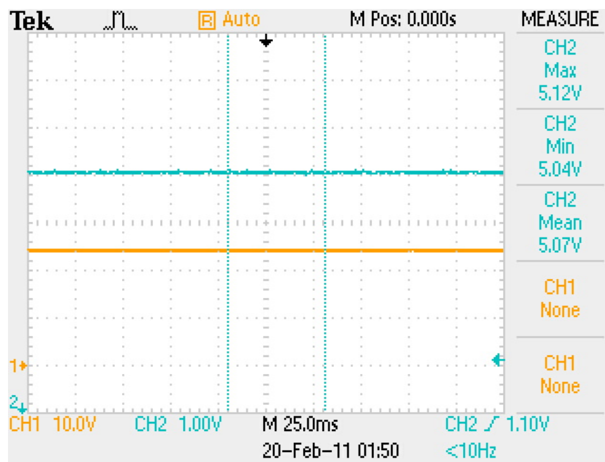

Figure 44-Open Load, 5V Peak and Settled Values

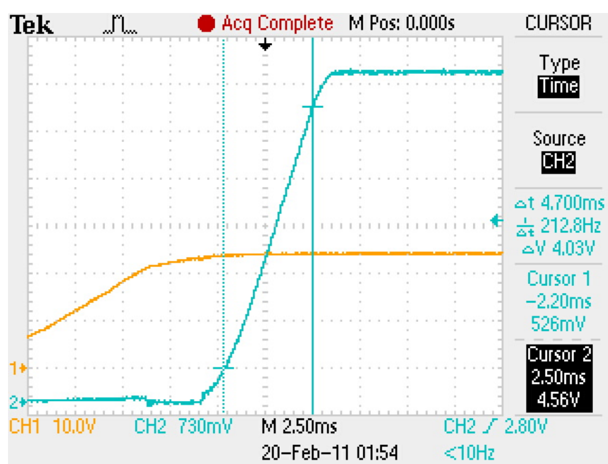

Figure 45-Open Load, 5V Rise Time

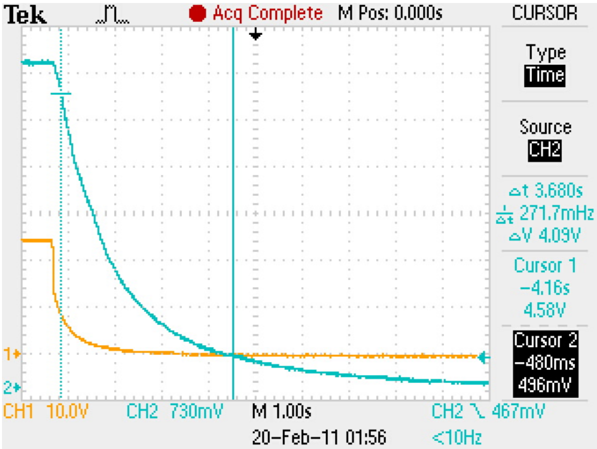

Figure 46-Open Load, 5V Fall Time

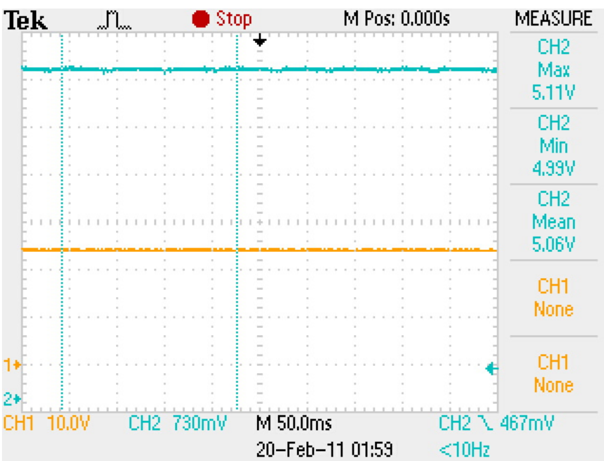

Figure 47-1.06A Load, 5V Peak and Settled Values

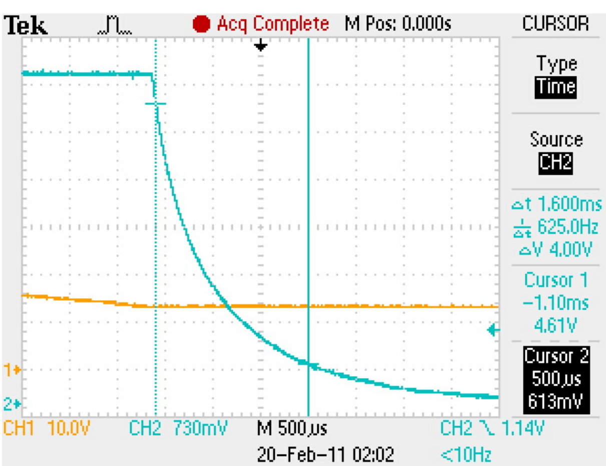

Figure 48-1.06A Load, 5V Fall Time

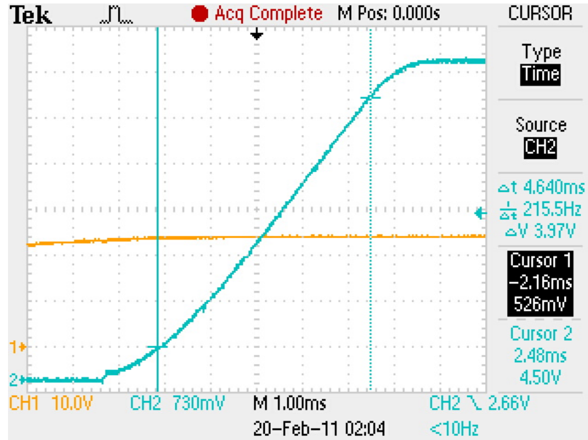

Figure 49-1.06A Load, 5V Rise Time

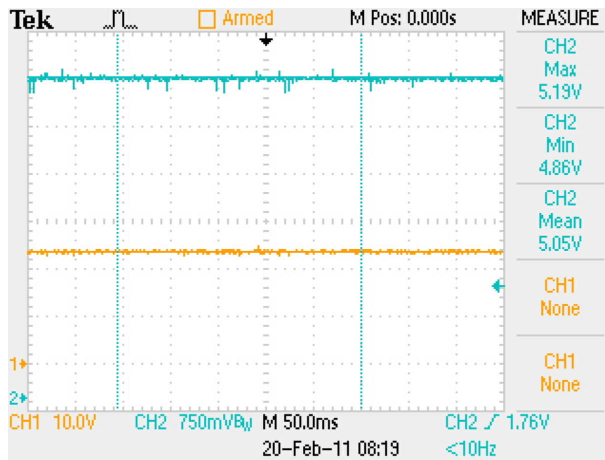

Figure 50-10.00A Load, 5V Peak and Settled Values

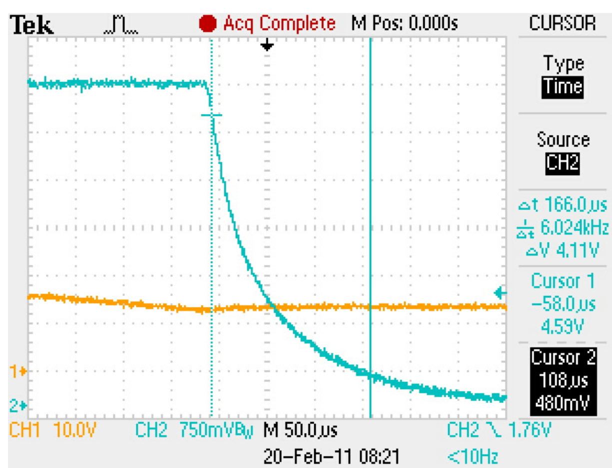

Figure 51-10.00A Load, 5V Fall Time

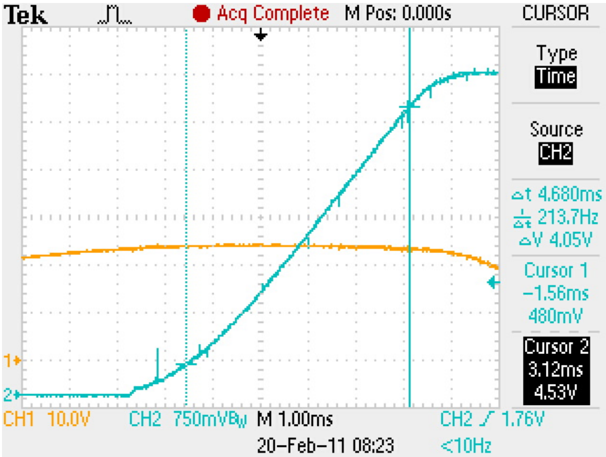

Figure 52-10.00A Load, 5V Rise Time

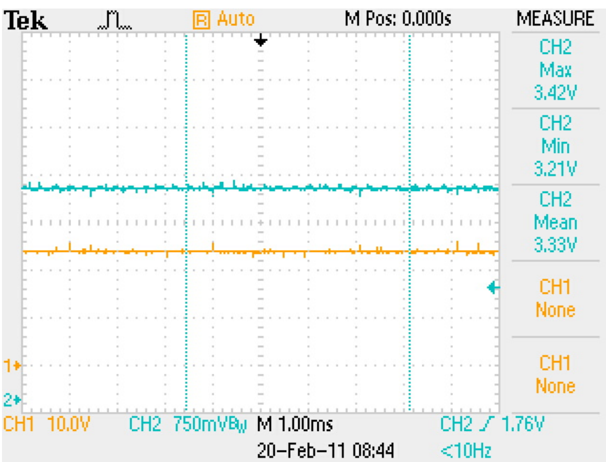

Figure 53-8.85A Load, 3.3V Peak and Settled Values

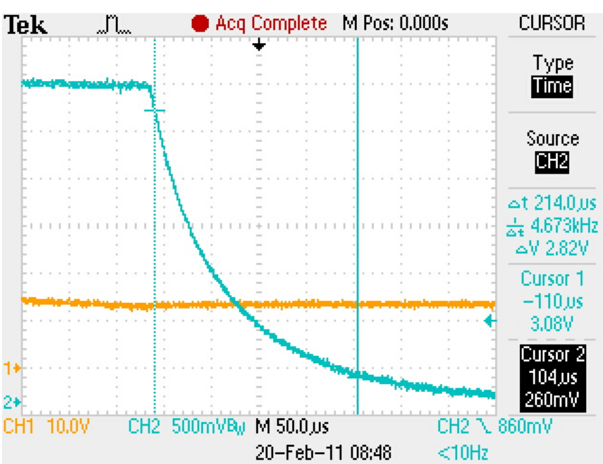

Figure 54-8.85A Load, 3.3V Fall Time

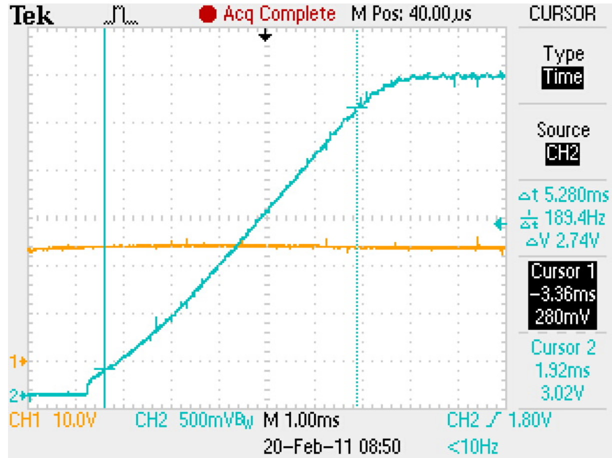

Figure 55-8.85A Load, 3.3V Rise Time

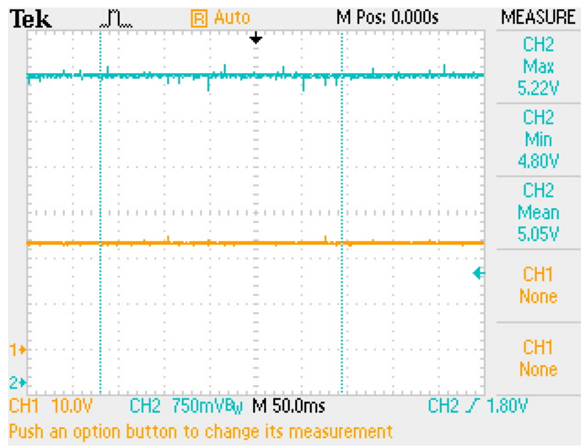

Figure 56-11.86A Load, 5V Peak and Settled Values

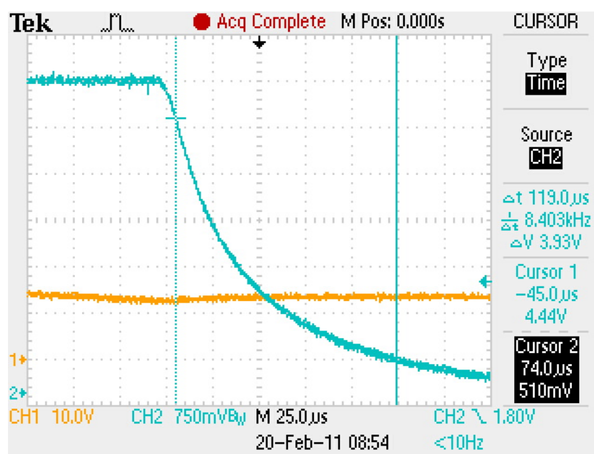

Figure 57-11.86A Load, 5V Fall Time

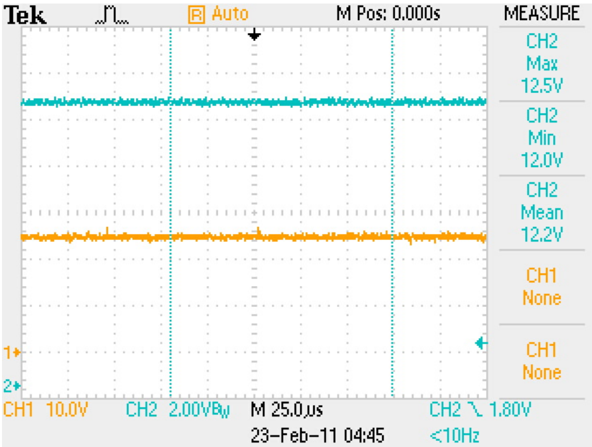

Figure 58-Open Load, 12V Peak and Settled Values

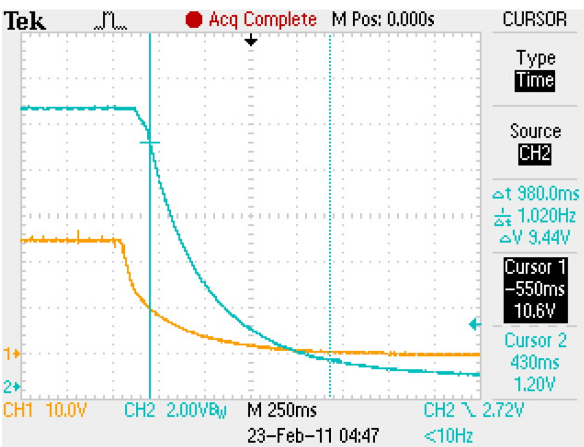

Figure 59-Open Load, 12V Fall Time

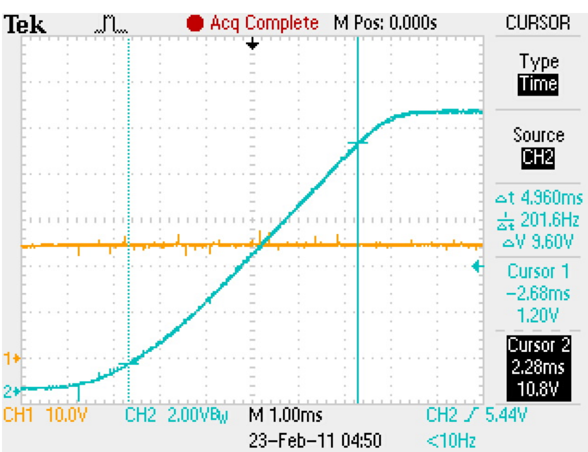

Figure 60-Open Load, 12V Rise Time

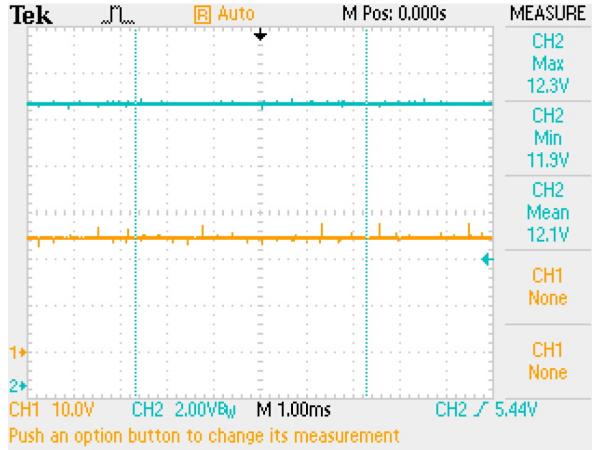

Figure 61-0.98A Load, 12V Peak and Settled Values

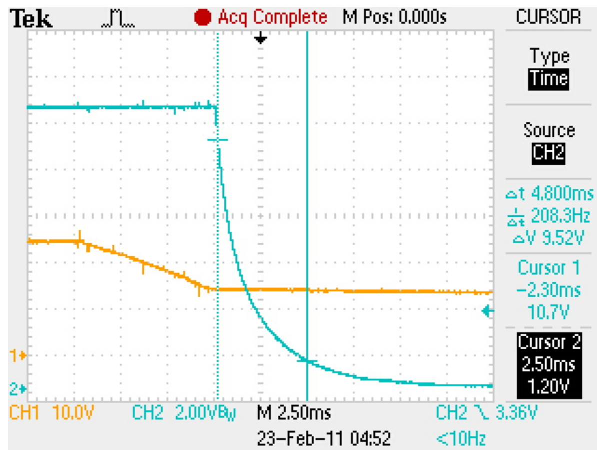

Figure 62-0.98A Load, 12V Fall Time

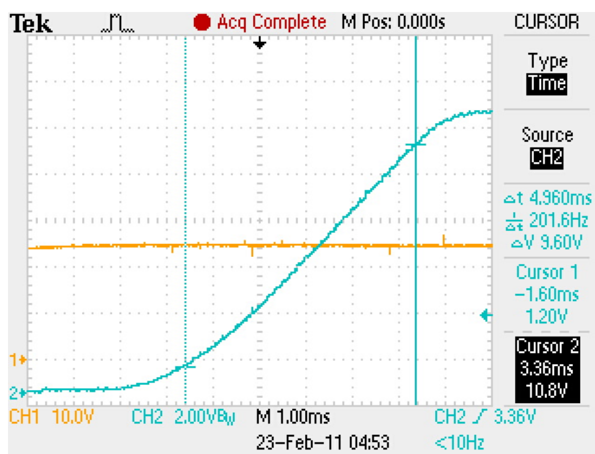

Figure 63- 0.98A Load, 12V Rise Time

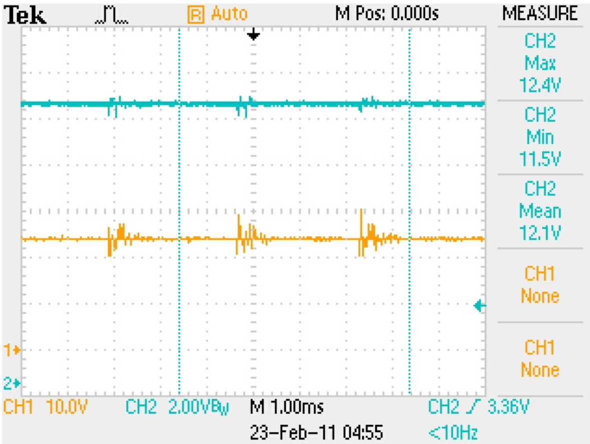

Figure 64-5.07A Load, 12V Peak and Settled Value

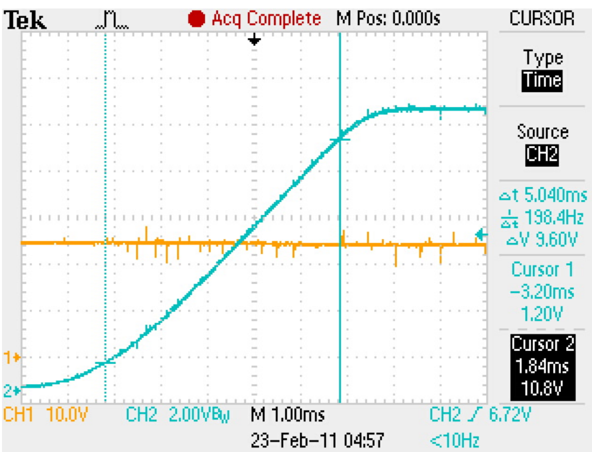

Figure 65-5.07A Load, 12V Rise Time

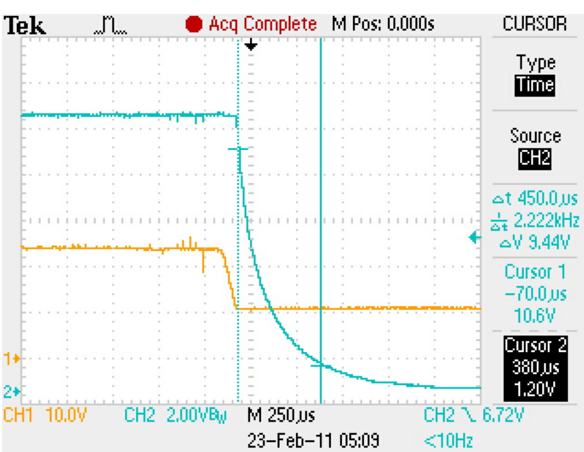

Figure 66-10.04A Load, 12V Fall Time

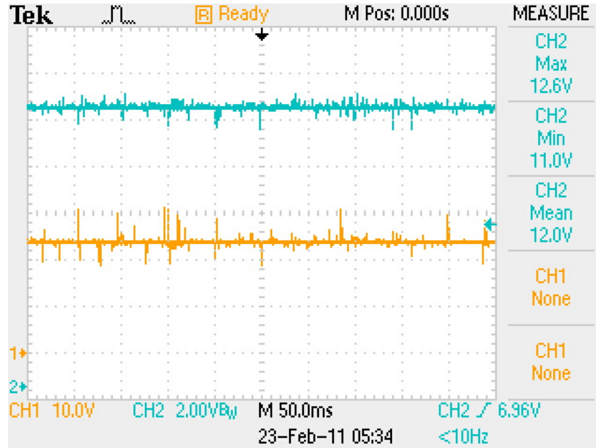

Figure 67-18.04A Load, 12V Peak and Settled Values

Appendix F- Meeting Minutes

MF RBE DC-DC Power Converter

Meeting Minutes

2/3/10 9am with Bitar in his office

- Need to do testing, first with open load; can be performed with bench top power supply input
- Ideas for loads: headlights, power resistors/power resistor networks, check with Emanuel for a resistor box,
- Thoughts on capacitive/inductive/dynamic loads

1/28/10 10am with Bitar in his office

- Still need to bring in order receipts for reimbursement
- By next week we hope to have fully populated the board
- Testing equipment was mentioned, perhaps not do a full load until use of car batteries is available
- Date on Friday at 10am in lou of Thursday at 9am due to snow complications, Thursdays at 9am is the set meeting time

12/6/10 1pm with Bitar in his office

- Decided on standard form factor: same size as existing model in Prometheus
- Deliverables for end of term: bare boards and status report

11/22/10 5pm with Bitar in his office

- Schematics have been completed and layout is going to begin
    - Print out a hard version of schematics
- Can we camera record the board making process as a favor for ECE 2799?
- Goal: Finish board manufacturing by the end of B term
- Ensure the space available in the robot for form factor (standard size/layout?)
- Discussion regarding heat sinks and power considerations
- Design verification testing?

11/12/10 1pm with Bitar in his office

- Meeting time for B term established as 1pm on Fridays
- Reconnection with Prometheus group is required now that new term has begun
- A thought for a good presentation would be a thermal model due to the thermal considerations that need to be accounted for
- Any and all parts that need to get purchased should be paid for and then reimbursed by Professor Bitar who will submit the paperwork for the school for official reimbursement

- Most of the components to the project have been ordered and are in the process of shipping, only purchasables are required

10/8/10 5 pm with Bitar in his office

- Deliverables for end of term
  - Title Page
  - Introduction
  - Background
  - Timeline
  - Design Decisions
  - Any Drawings and Schematics
- Design focus for the time being will only include the 24 volt as an input to limit scope of project.
- Next logical Step is to secure parts before beginning layout of printed circuit board.
- Prototype on Printed Circuits instead of bread boards due to the sensitivity of the circuitry and thermal reasons.
- Jim absent due to wedding, meeting notes completed by Remy.

10/1/10 5pm with Bitar in his office

- Discussed thoughts on overall design, decided on designing one supply for all 4-5 voltages at a smaller current rating, does not require more footprint than a single voltage due to minimum fan layout size
- The general design for smaller wattages would cover requirements for Prometheus processing card as well as the diversity required for other robot designs
- Discussion on fan control and stability

9/27/10 4pm with Bitar, DCDCMQP, Felipe, Padir in AK318

- Promoted idea around modular supplies for individual requirements within robotics systems
  - Professor Padir was ok with the thought outside of being concerned regarding the amount of power the GPU processor consumes
- Decided on separating into two projects: one specifically for the high current processing card, one for smaller modules for sensors, safety, router, etc.
- Look into scenarios for power usage analysis?
- Need to investigate generic off-shelf 24->12V power supplies for GPU card and other modules
- Added output of 18V potentially for smaller peripherals to run other robotics motors

9/24/10 5pm with Professor Bitar in his Office

- Need to get a block diagram for system inside the DC/DC supply
- Redefined project: instead of doing one very large wattage power supply make smaller modular supplies at lower wattage
- Agenda:
  - Meet with Padir/robot group to determine concerns on modular design
  - In meeting, need to fully define the project

9/24/10 1pm with Prometheus MQP Group

- General questions for background were passed out to some members and to advisor group
- Power Supply may not make it into the robot this year but is desired for both future generations and for other projects with similar goals
- Professor Padir does not wish to continue buying power supplies and would like a one size fits all sort of mentality for projects
- Size, weight, standardized connectors, heat output, ruggedized, and efficiency are serious considerations

9/20/2010 5pm with Professor Bitar in his Office

- Established weekly meeting schedule with Professor Bitar in his office on Mondays at 5pm
- Additional meeting setup for Friday 9/24/2010 at 5pm to go over system requirements
- Meeting 9/24/10 in AK 218 at 5pm with Prometheus group (robotics mqp group)

Agenda for next meeting:

1. System Requirements
   a. Determine the Voltage, Current, Load Profiles, mechanical space, and minimum requirements
2. Establish a Schedule with:
   a. Prometheus MQP Robotics Group
   b. Professor Padir
   c. Us individually
3. Detailed specs for our personal supply design
4. High Level System block diagram (I/O at least) for basic project layout
5. Artist's rendition for physical layout and space requirements

9/7/2010 2pm with Professor Bitar in his Office

- Reassured topic applicability and finished registration paperwork, handed in to Marge Rancone in Registrar's office
- Bitar is overbooked and plans on taking more of a back seat in terms of technical details
- Discussed general premise of supplying the necessary voltages for robots: +/- 12, +/-5, 1.3, 1.5
- Recommend looking into older version of power supply in order to check for efficiency
- Talked about potentially modularizing the smaller voltage supplies to increase potential current supply

Agenda for next meeting:

- 〉 Determine a list of questions that we require answers to from Prof. Padir/the Robotics MQP group

Appendix H-Users Guide

The operation of the power supply is very simple. First, attach the load to the output terminals as required. After this then connect the power to the input terminals. Avoid hot swapping loads when possible as large capacitive loads being brought on to the operating supply can cause momentary instability. This is due to the supply having to correct for the sudden voltage drop due to this. For optimal use ensure there is a power switch in line with the source to the power supply as there is no easy way to turn the supply of at the supply level as this was designed to be similar to a ATX type PC power supply. The picture below shows the inputs and outputs for the power supply.

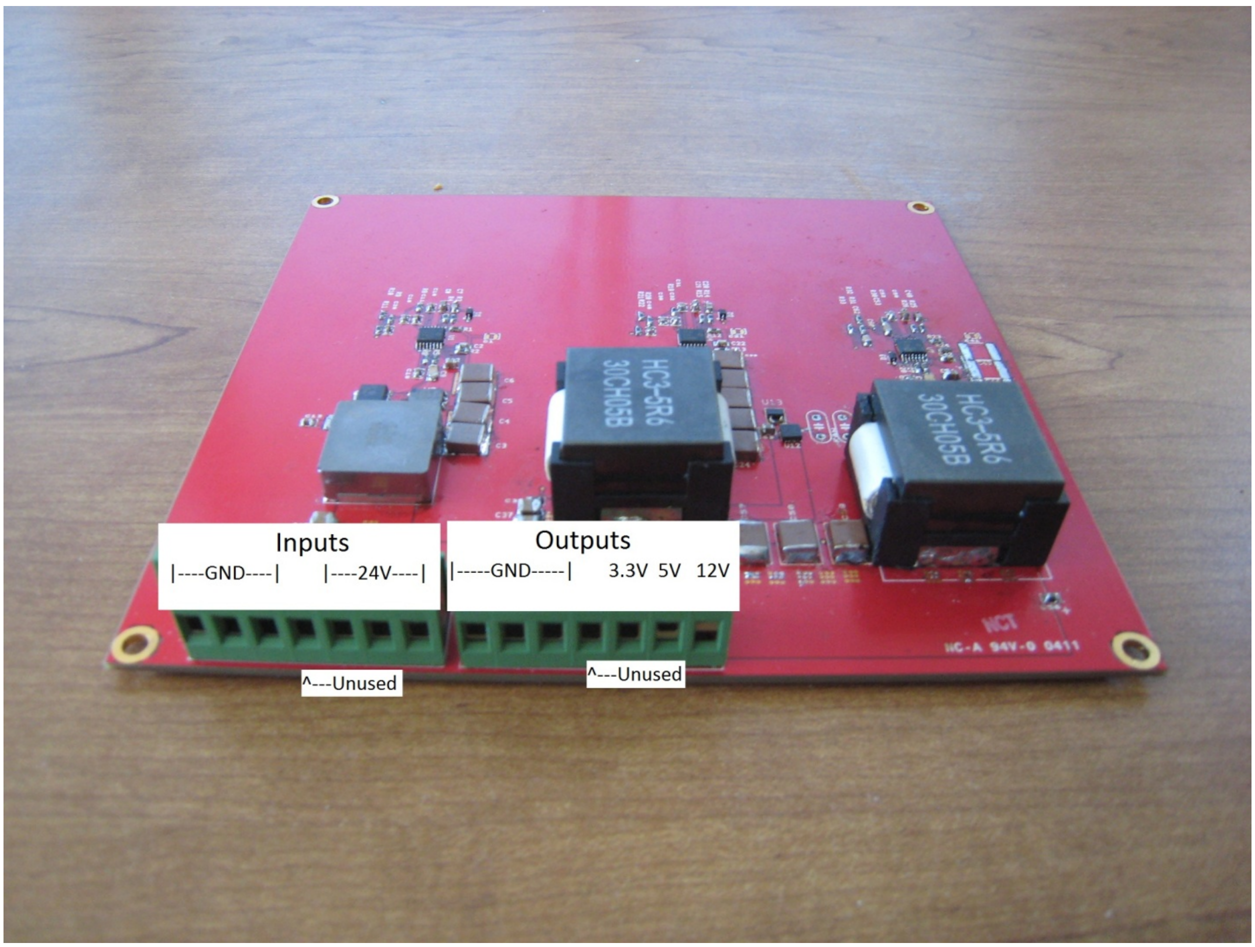

Figure 68-Input and Outputs Terminals

There are rated maximums that must be observed. Do not use a voltage over 40 volts as the input because of the possibility of damaging the circuit. The minimum voltage to operate will be below

14 volts. The supply will however not turn on below 18 volts, as there is not enough voltage to have the control circuitry to begin working to operate its internal power supplies. A quick reference guide is available for your convenience at the bottom of this page. This power supply is intended to run at high currents and will get warm but this is normal. Do not touch parts while the supply is operating. Please note that these currents are continuous they are capable of peak currents higher than this but the actual peak currents were not tested, as it would be destructive to the supply. For further technical information please consult the TPS40055 datasheet.

Max Input Voltage	40V
Max Current 12V	20A
Max Current 5V	20A
Max Current 3.3V	15A

Minimum Turn On Voltage	18 Volts
Minimum Operating Voltage	14 Volts

Table 13-Operational Limits